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HEBC

LARP

Hollow Electron Beam Collimator

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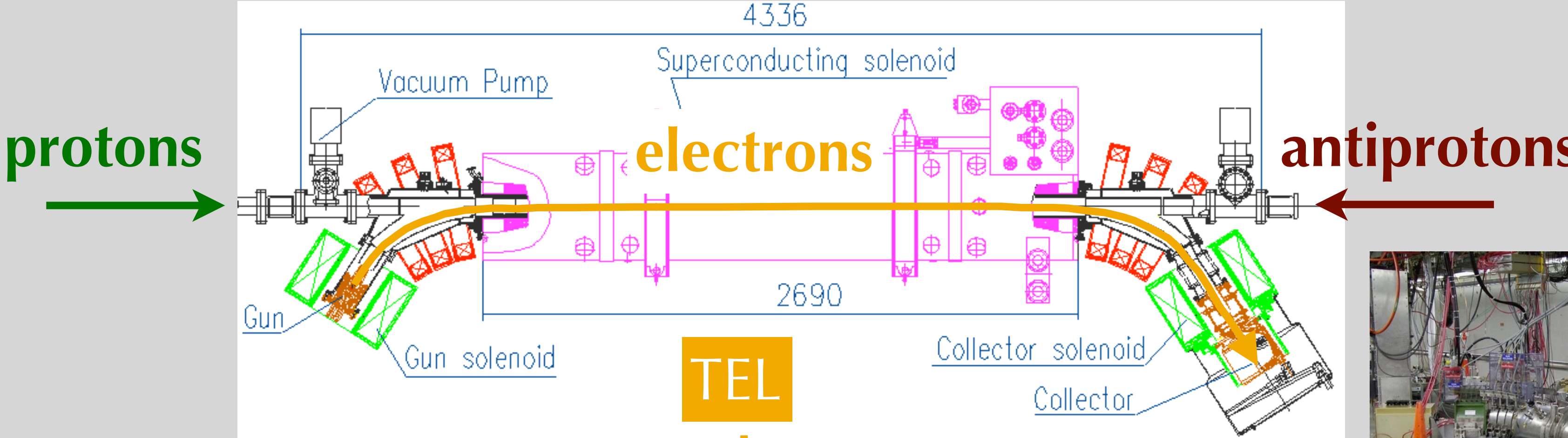
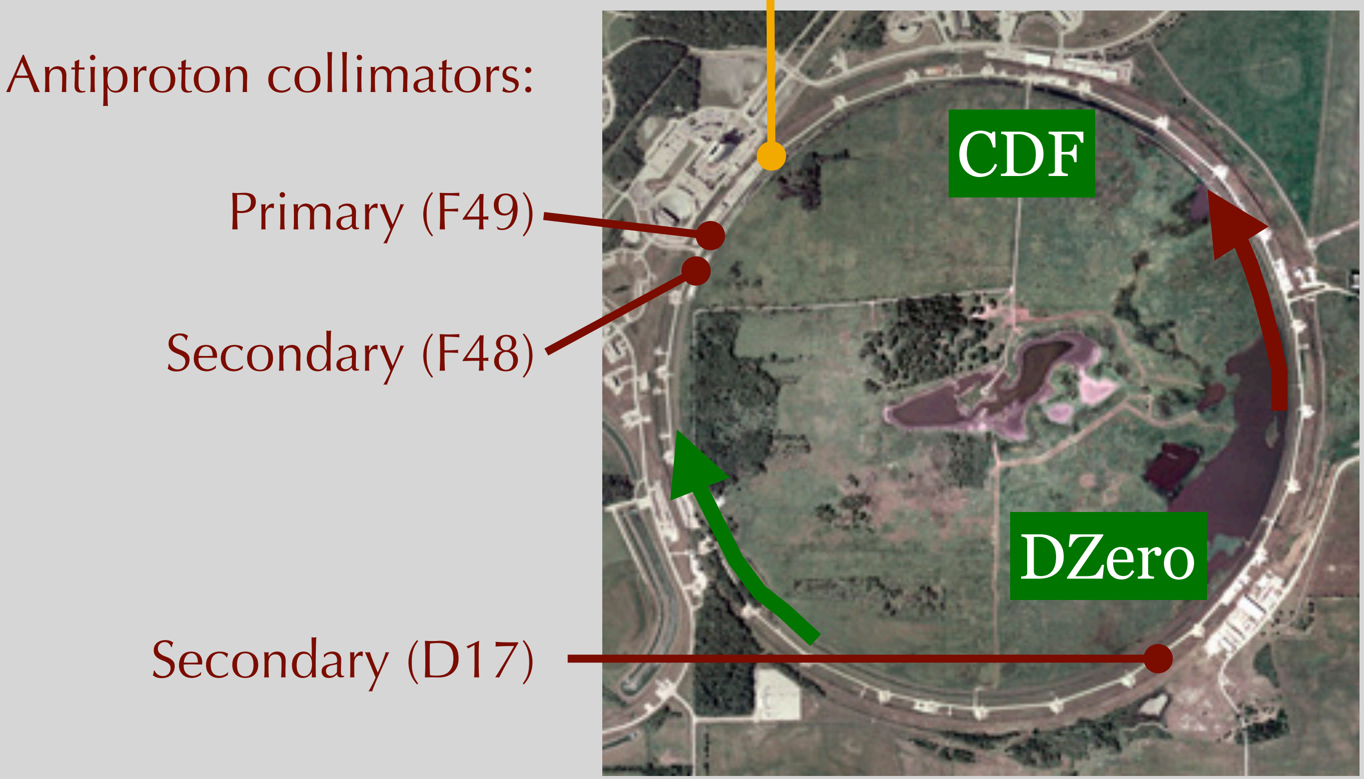
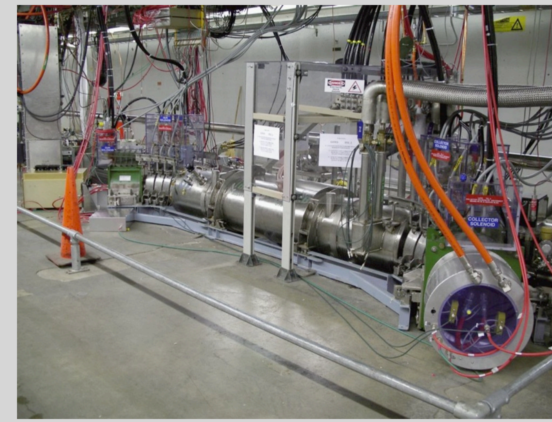
2nd Joint HiLumi LHC Meeting / LARP Collaboration Meeting 18
Fermilab, 7-9 May 2012

Layout of the beams in the Tevatron



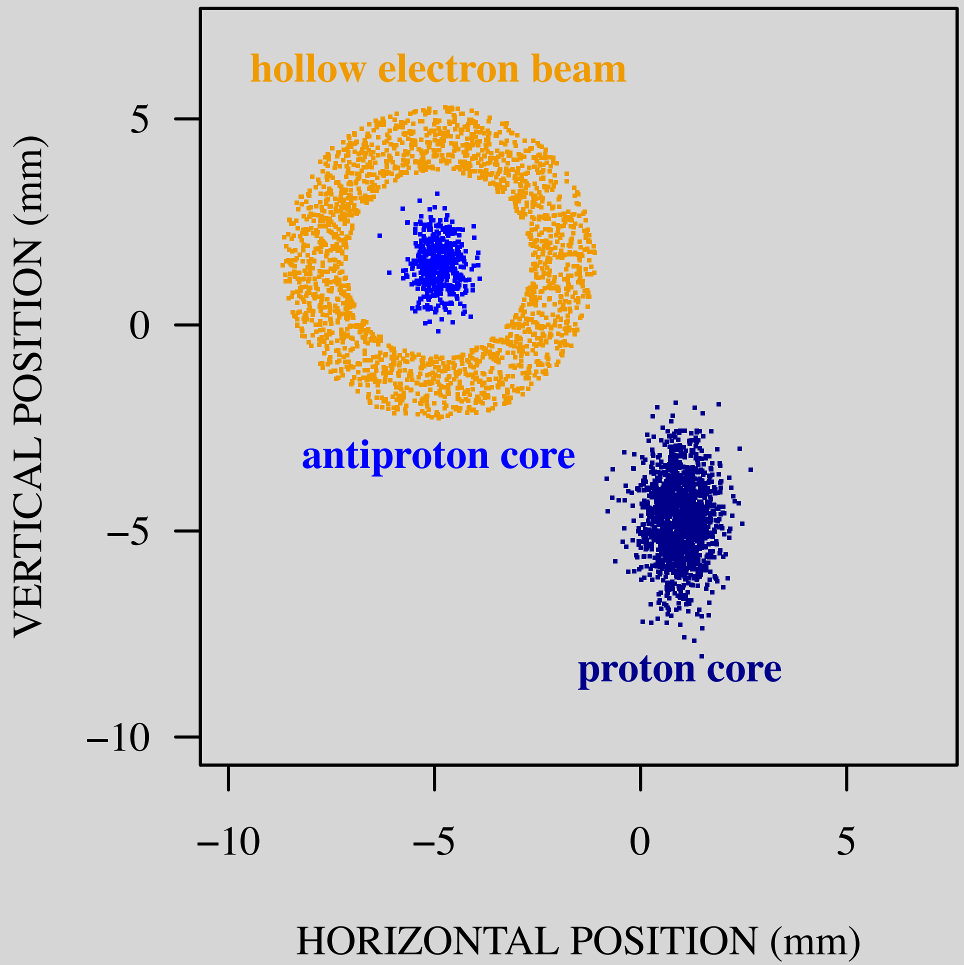


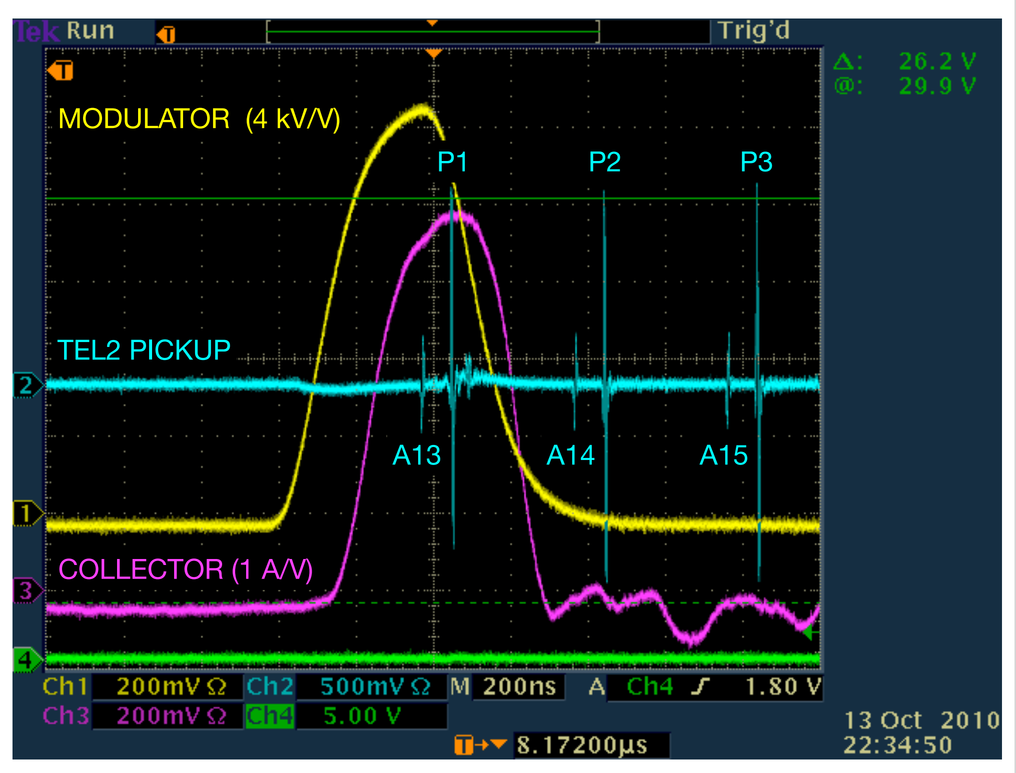


Tevatron electron lens (TEL2)

Layout of the beams in the Tevatron electron lens

Transverse separation is 9 mm



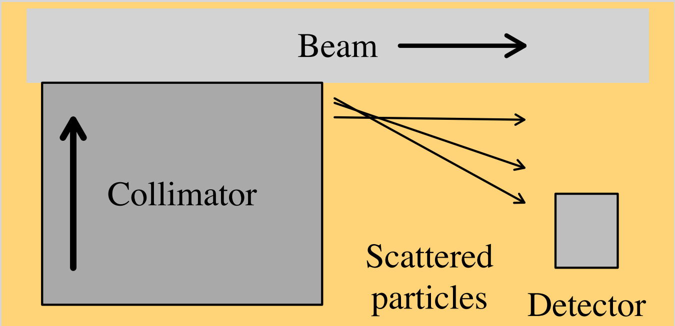


Pulsed electron beam can be synchronized with any group of bunches

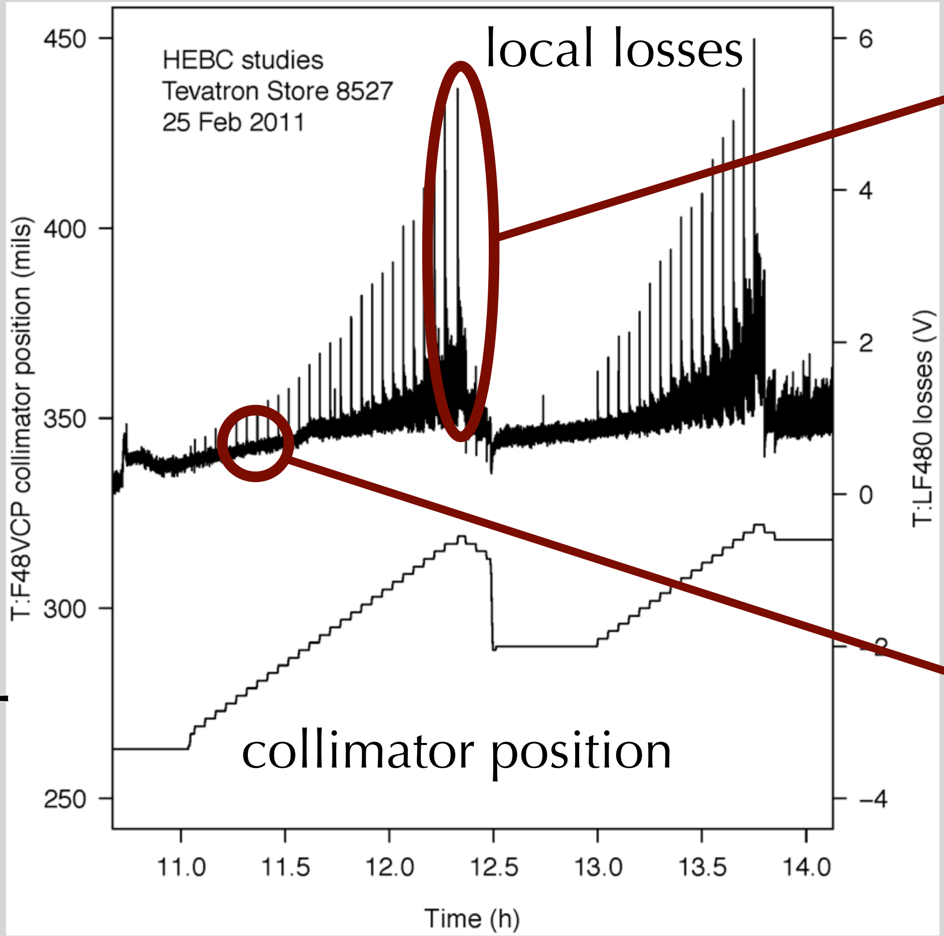
Status of hollow electron beam collimation

- Tevatron experiments (Oct. ‘10 - Sep. ’11) provided experimental foundation
- Main results
  - **compatibility with collider operations**
  - **alignment** is reliable and reproducible
  - **smooth halo removal**
  - **removal rate vs. particle amplitude**
  - **negligible effects on the core** (particle removal or emittance growth)
  - transverse beam **diffusion enhancement**
  - **suppression of loss-rate fluctuations** (beam jitter, tune changes)
  - effects on **collimation efficiency**
- First results:
  - Phys. Rev. Lett. **107**, 084802 (2011)
  - IPAC11, p. 1939
  - APS/DPF Proceedings, arXiv:1110.0144 [physics.acc-ph]

Diffusion rate vs. amplitude from collimator scans

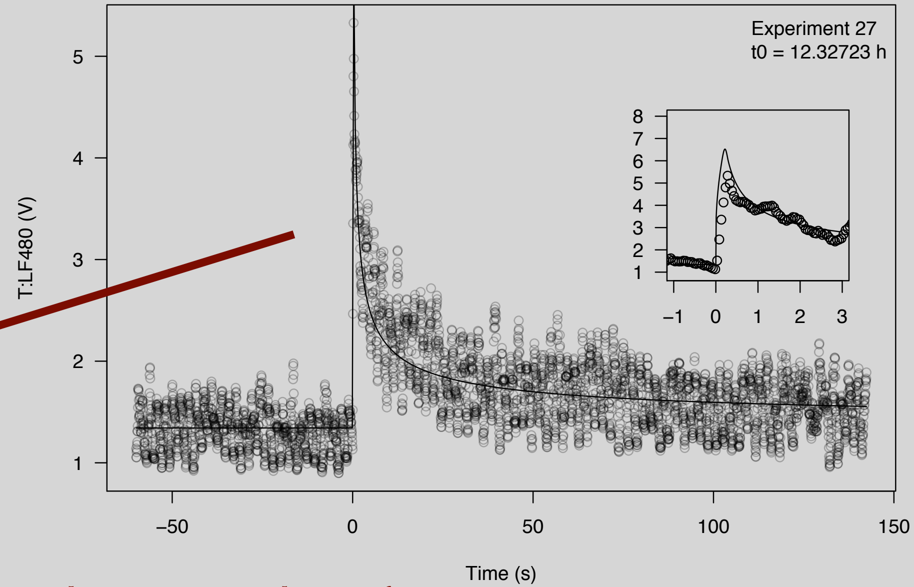


up towards beam axis

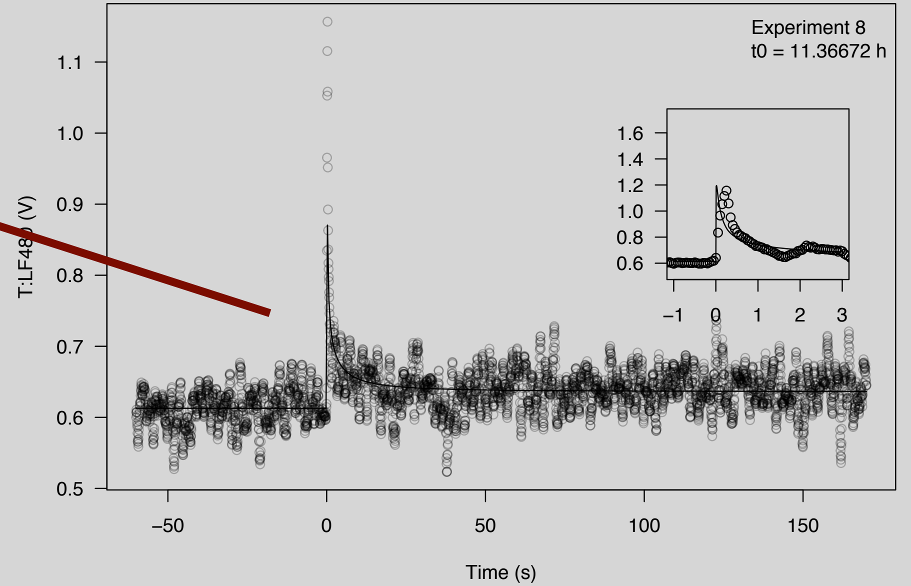


IPAC11, p. 1882
arXiv:1108.5010 [physics.acc-ph]

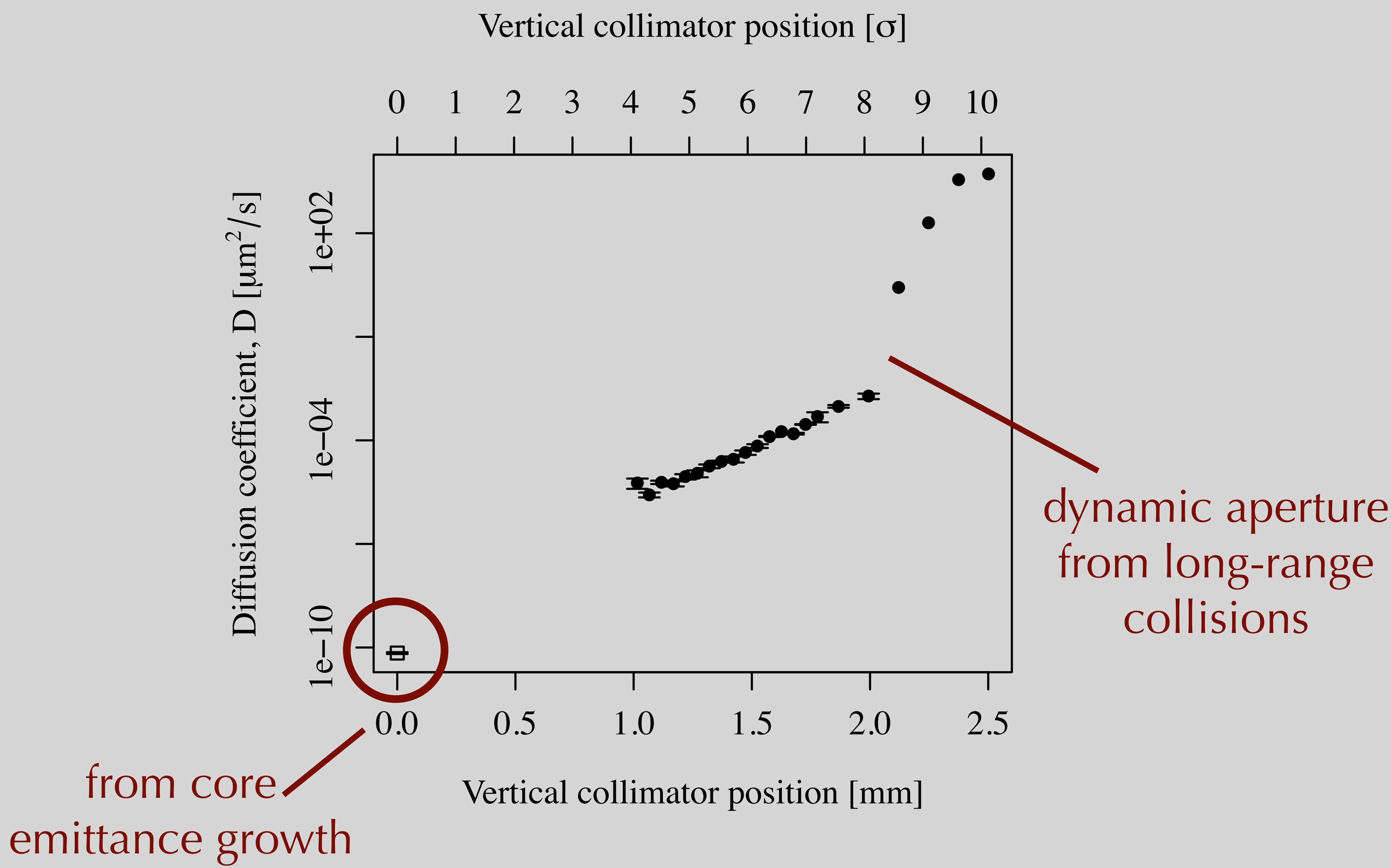
Mess and Seidel, NIMA **351**, 279 (1994)



Tails repopulate faster at
large amplitudes (higher diffusion rate)

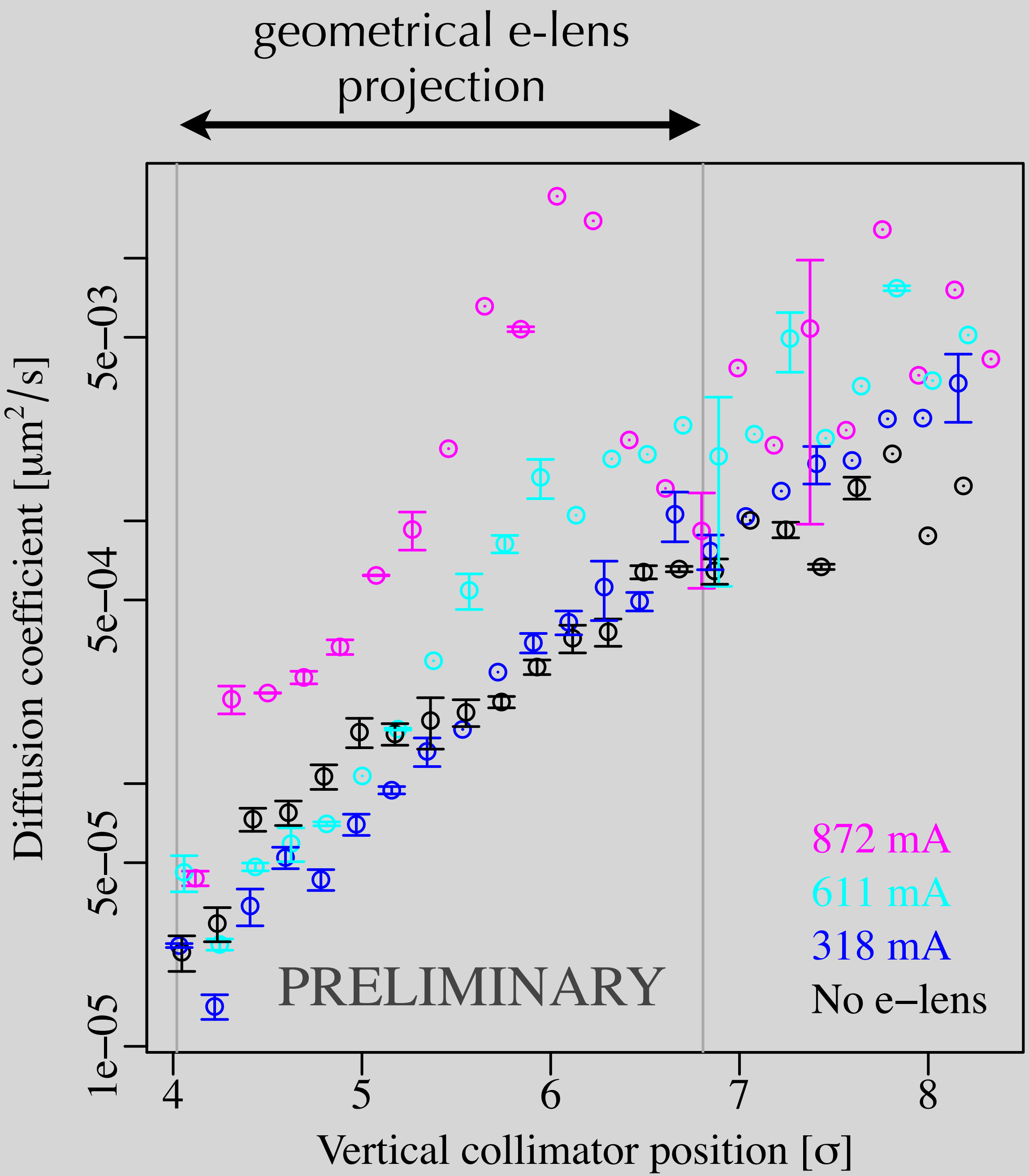


Halo diffusion measurements in the Tevatron



Plan to compare with LHC and RHIC

Measured effect of the electron lens on diffusion in the Tevatron



Large diffusion enhancement in halo region

Current directions

Numerical simulations
  Understanding of Tevatron observations
  Predictions for LHC
  Main observables
    halo removal rates
    diffusion enhancement

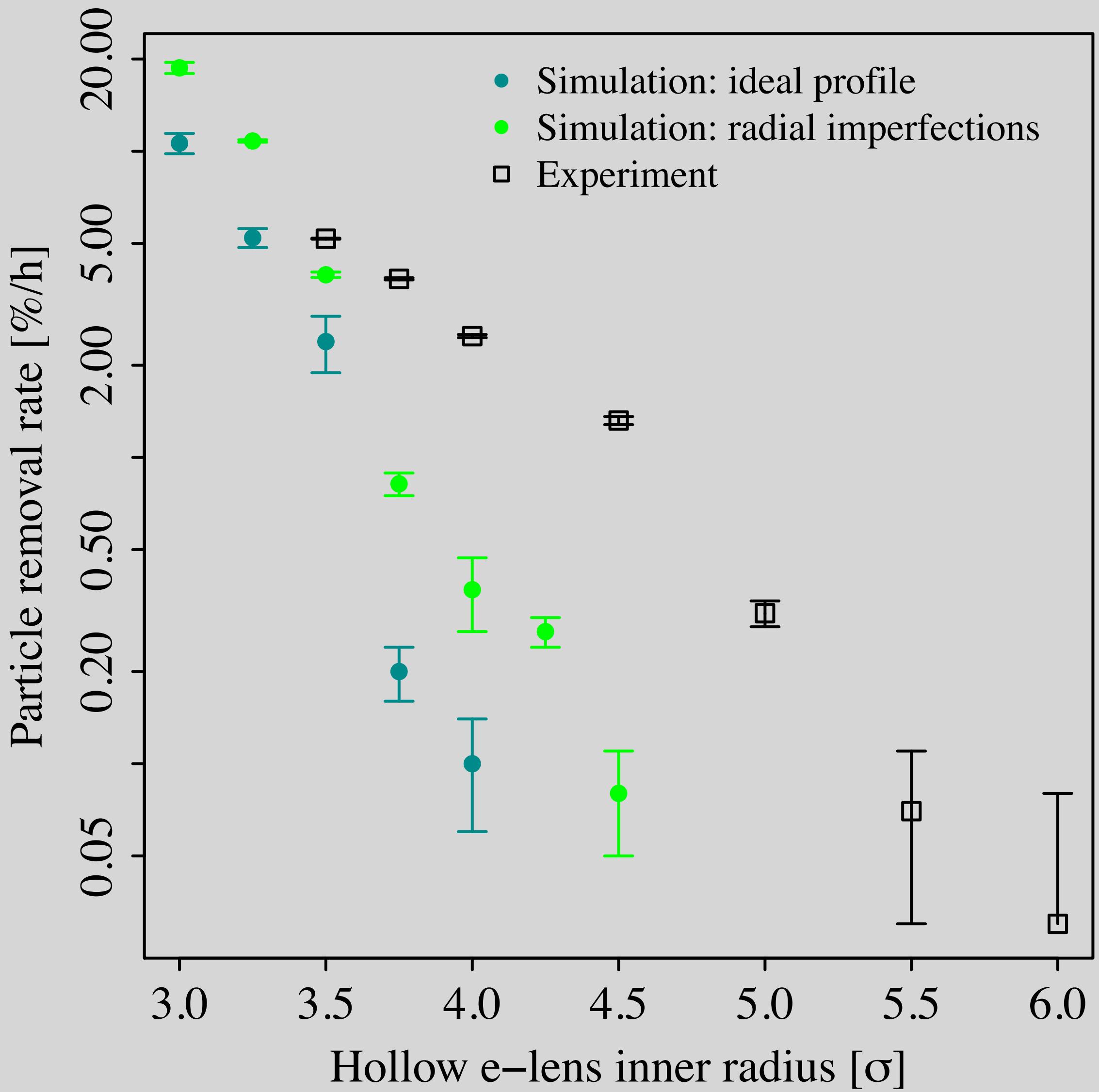
Development of **hollow electron guns**
  Preserve design/testing technology
  Produce prototypes for LHC

Study possible TEL2 **integration in LHC**
  Preparatory work at FNAL
  Scientific and technical aspects

Tracking simulations of HEBC dynamics

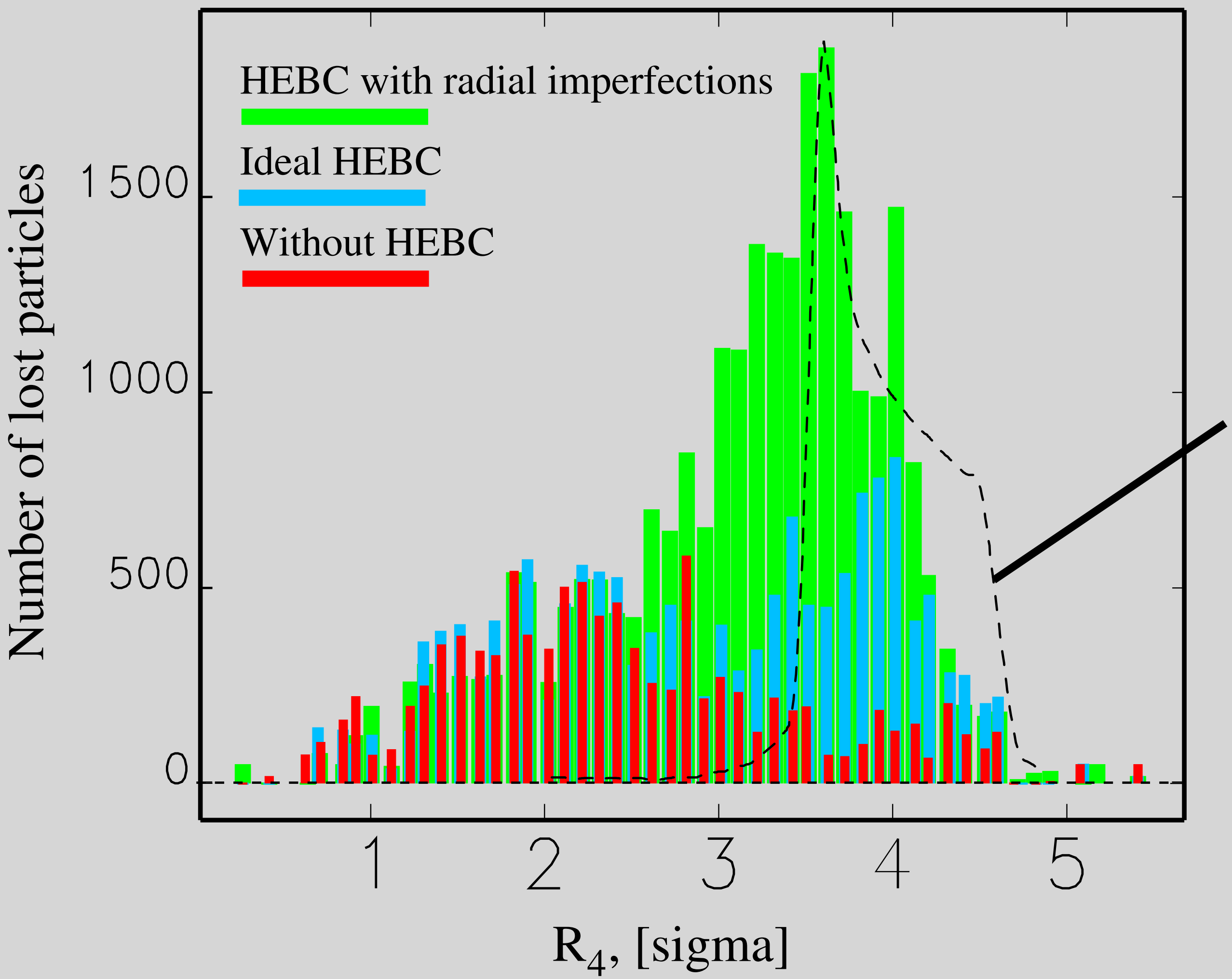
- Developed electron lens model in Lifetrac
- Capability to include e-beam imperfections and misalignments
- Includes noise, nonlinearities, beam-beam
- Collimation scheme is simplified
- Benefits from existing SixTrack / Lifetrac benchmarking for LHC
- May be used to study effect of e-lens intensity, hole radius, pulsing pattern on
  - particle removal rates
  - diffusion rates
  - resonances (frequency map analysis)
- Next, include e-lens in SixTrack (which has description of LHC collimation)

Lifetrac simulation of removal rates in the Tevatron



Lifetrac simulation of removal rates in the Tevatron

Which particles are removed?



Initial 4D amplitude of lost particles

sample e-lens profile

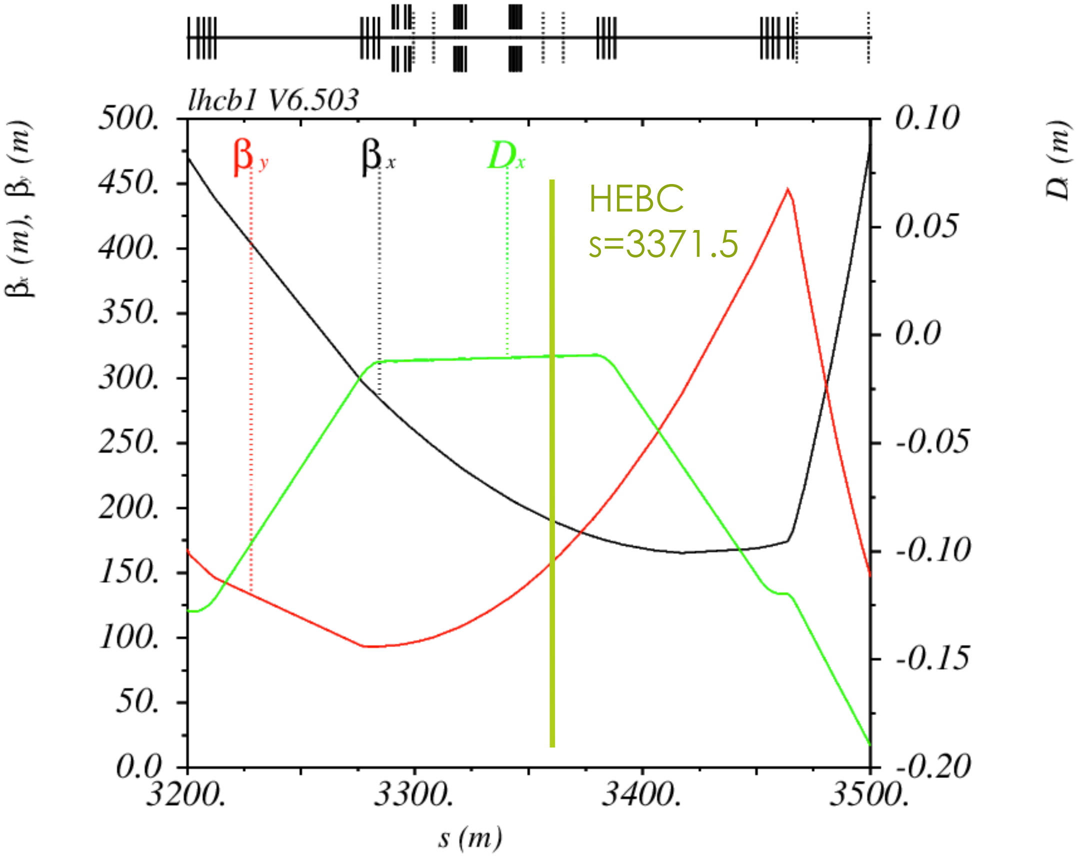
Particles removed from halo

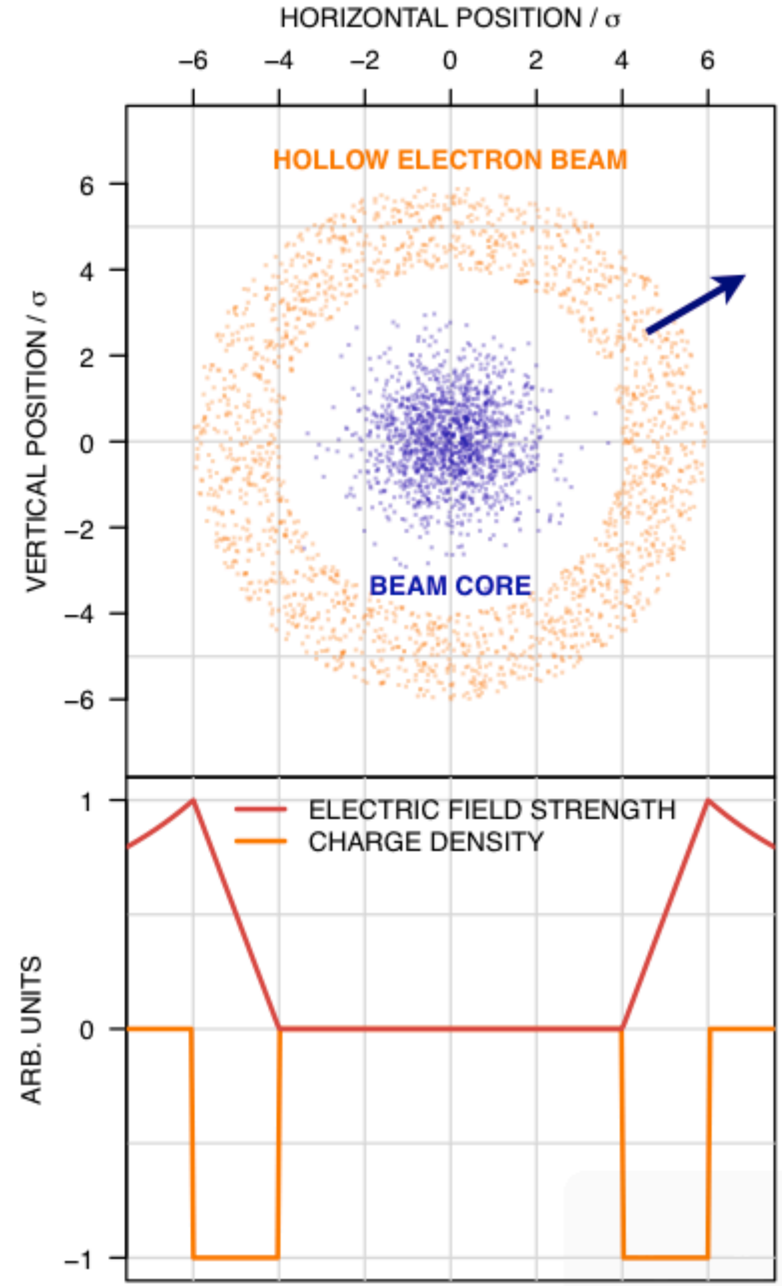
Halo removal sensitive to radial profile and halo population, which are hard to measure

Simulation of HEBC at LHC

- The goal is to produce preliminary estimate of the effect of TEL on LHC beam
  - Main question: What magnitude of the removal rate for halo particles can be expected for realistic parameters of TEL and LHC beams?
  - TEL beam is assumed ideally axially-symmetric, hence no effect on the LHC beam core.
  - These simulations do not include the full collimator set-up (further steps).
- LHC Model
  - Lattice V6.503 with errors and beam-beam
  - HEBC element installed in RB46 at 39.26 m from IP4
  - Single aperture restriction at 6σ (both x and y)
  - 1000 macro-particles, initial distribution – a ring with $r1=4\sigma$, $r2=6\sigma$
- HEBC Model
  - Constant density, Inner beam radius 4σ
  - Current up to 2A (kick=0.15 μrad)

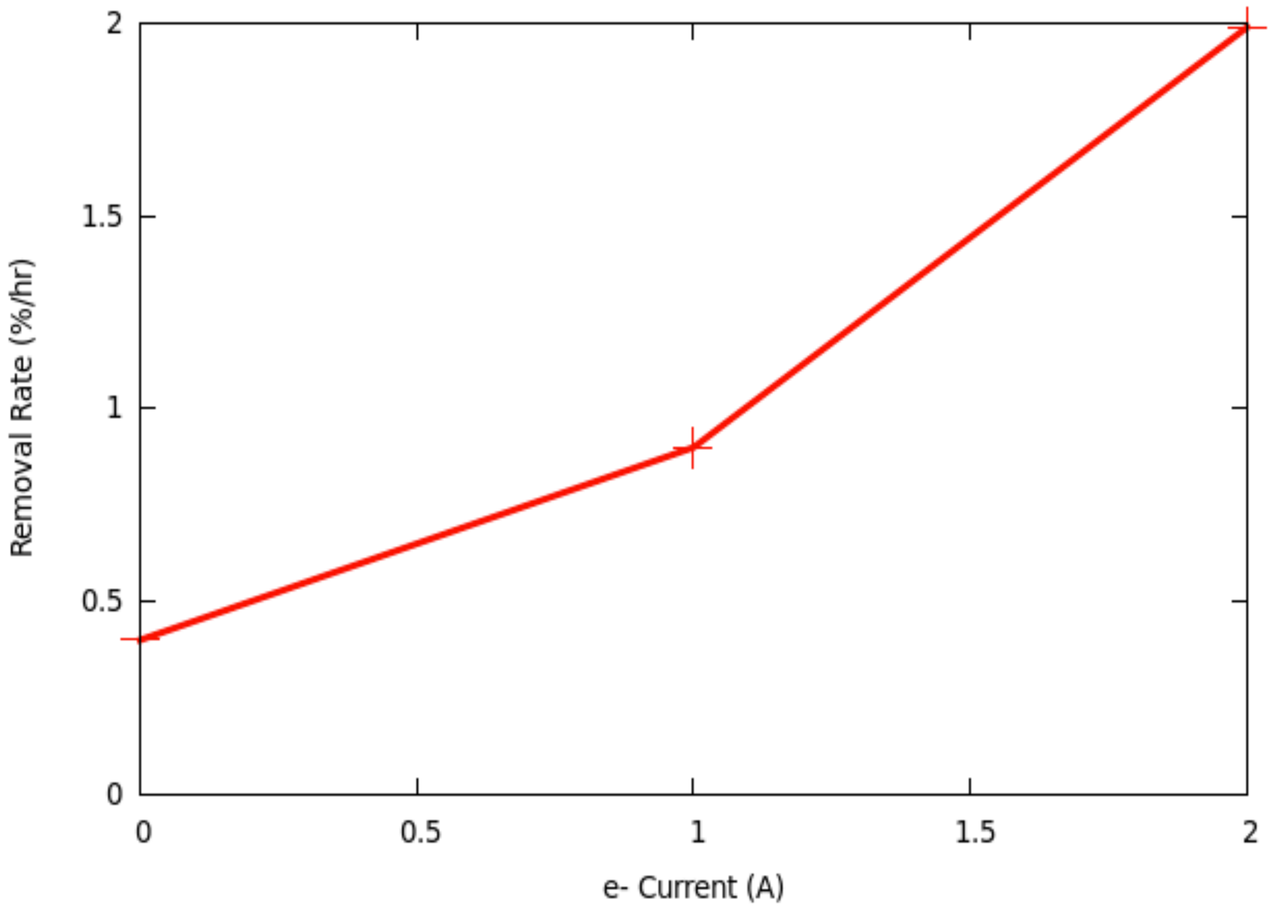
Model Parameters





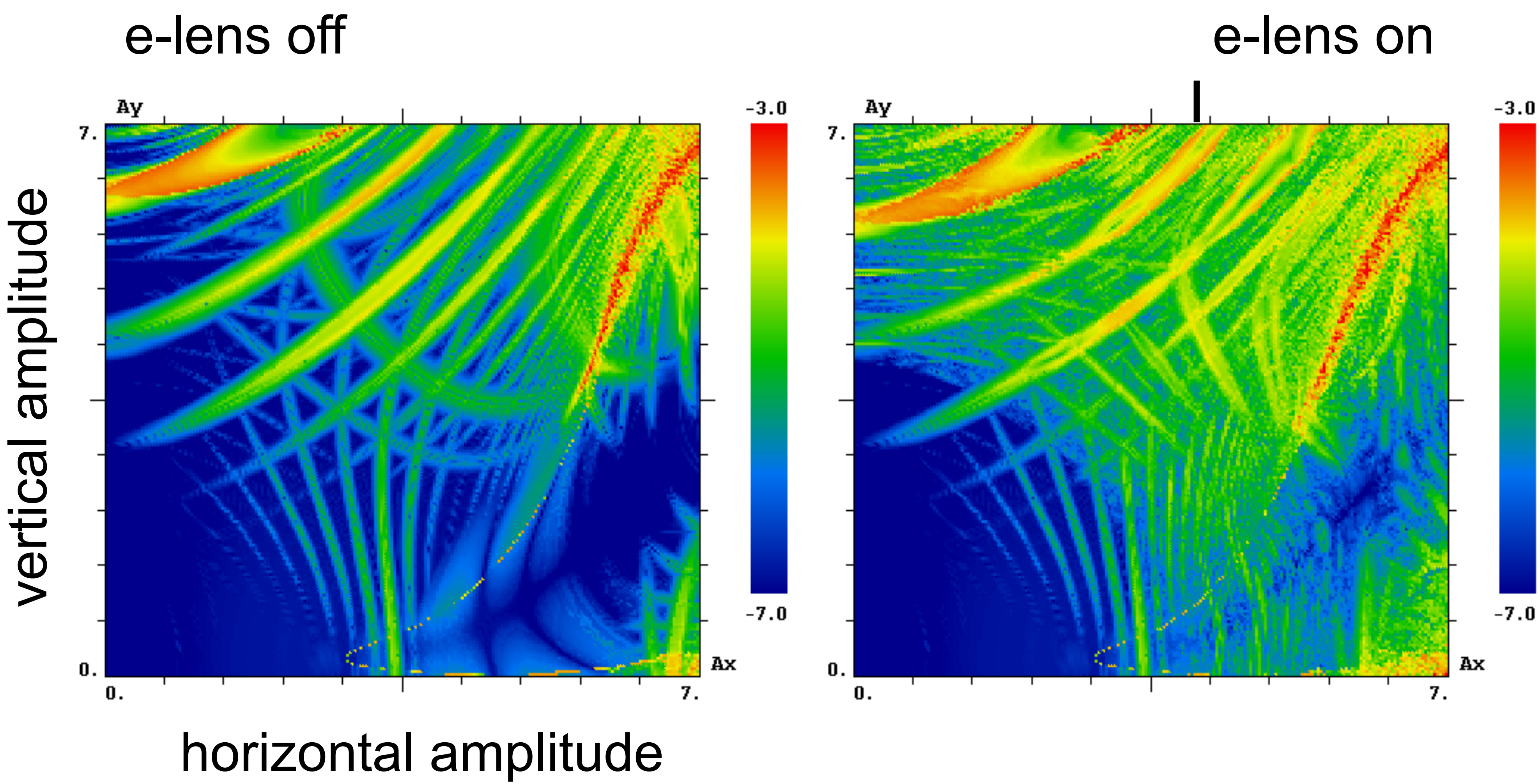
- β=187 m
- LHC beam size at HEBC σp=0.26 mm
- HEBC beam radius r1=1 mm
- E- current 2A, Magnetic field 4T
- Maximum kick 0.15 μrad

LHC HEBC Simulation Results



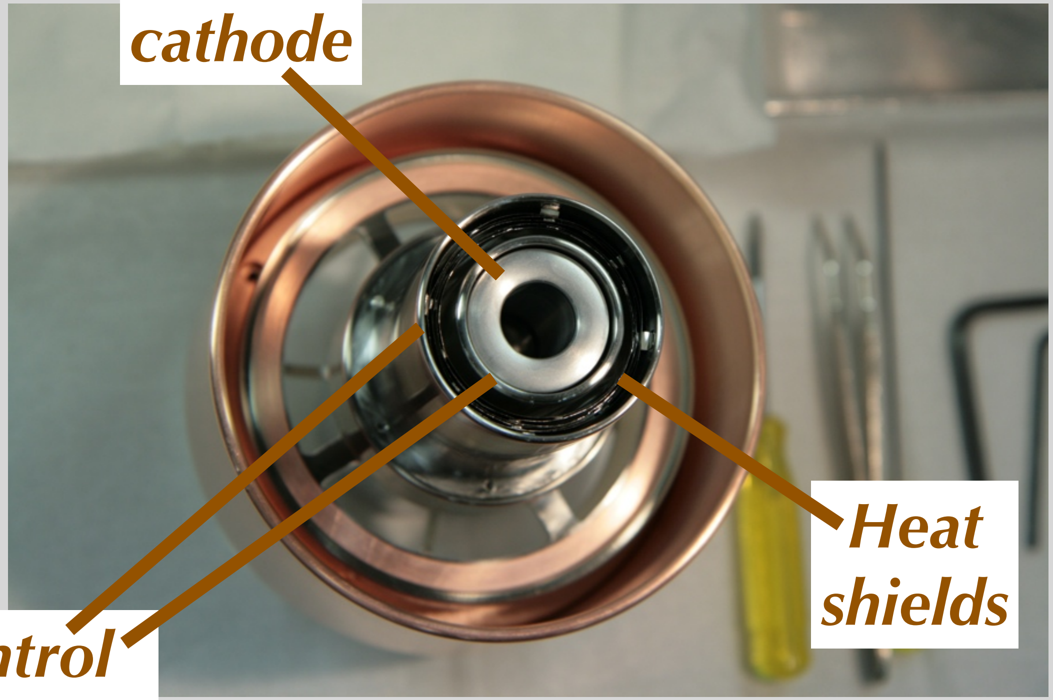
- Long-term tracking shows that HEBC increases the removal rate of halo particles by a factor of 2 for realistic beam parameters
  - Conservative estimate, imperfections will enhance the effect.

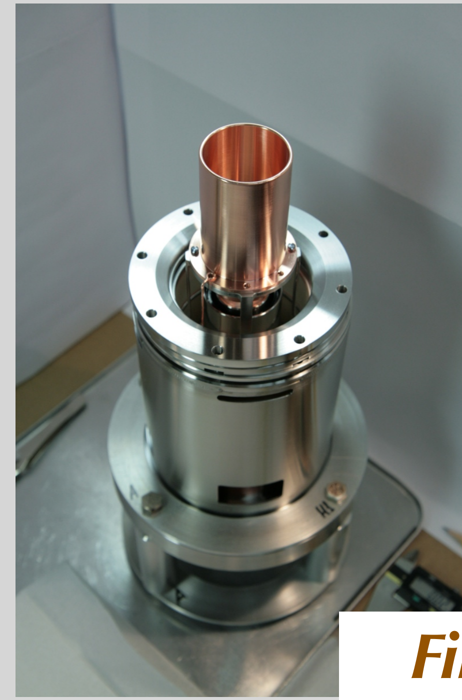
LHC HEBC Simulation Results



- Frequency map analysis (FMA) shows new resonances and overall tune jitter for particles between 4 and 6 sigma

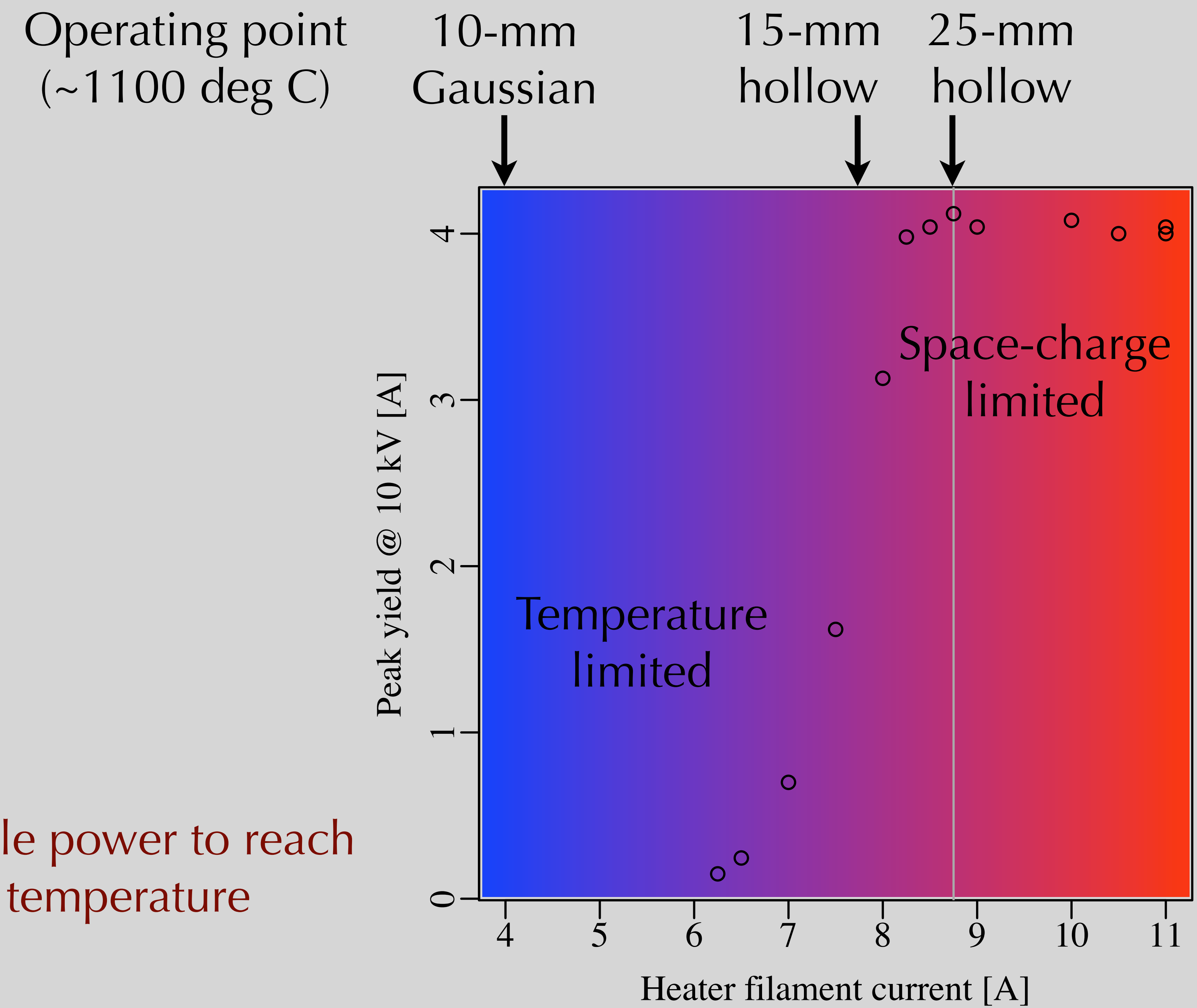
New 25-mm hollow gun





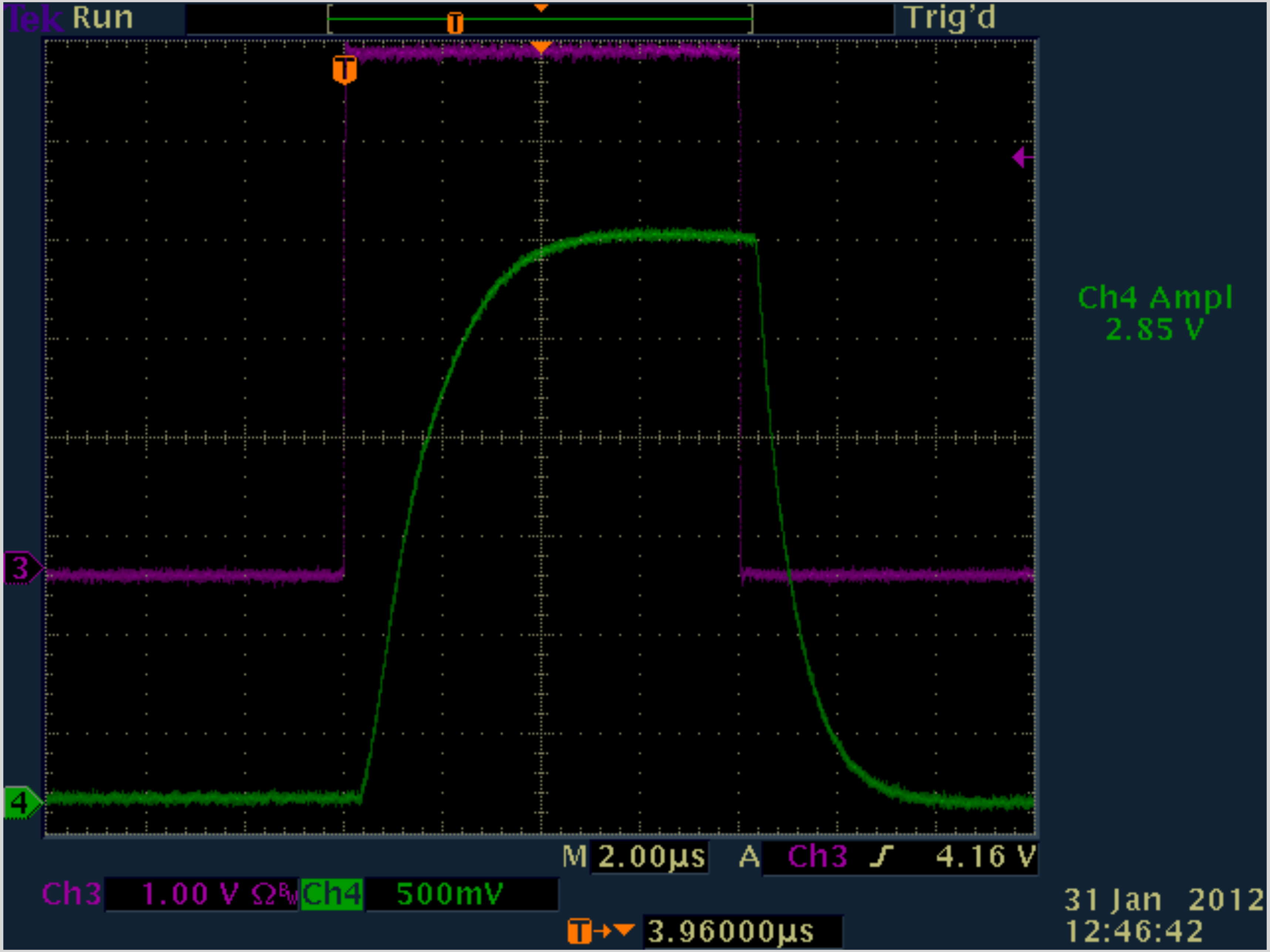
- 25 mm outer diameter, 13.5 inner diameter
- Designed with LHC in mind: 2.2 A at 5 kV, 6.3 A at 10 kV
- Goal: test technical feasibility of stronger scraper
- Characterized at Fermilab electron-lens test stand

25-mm hollow electron gun: yield vs. temperature

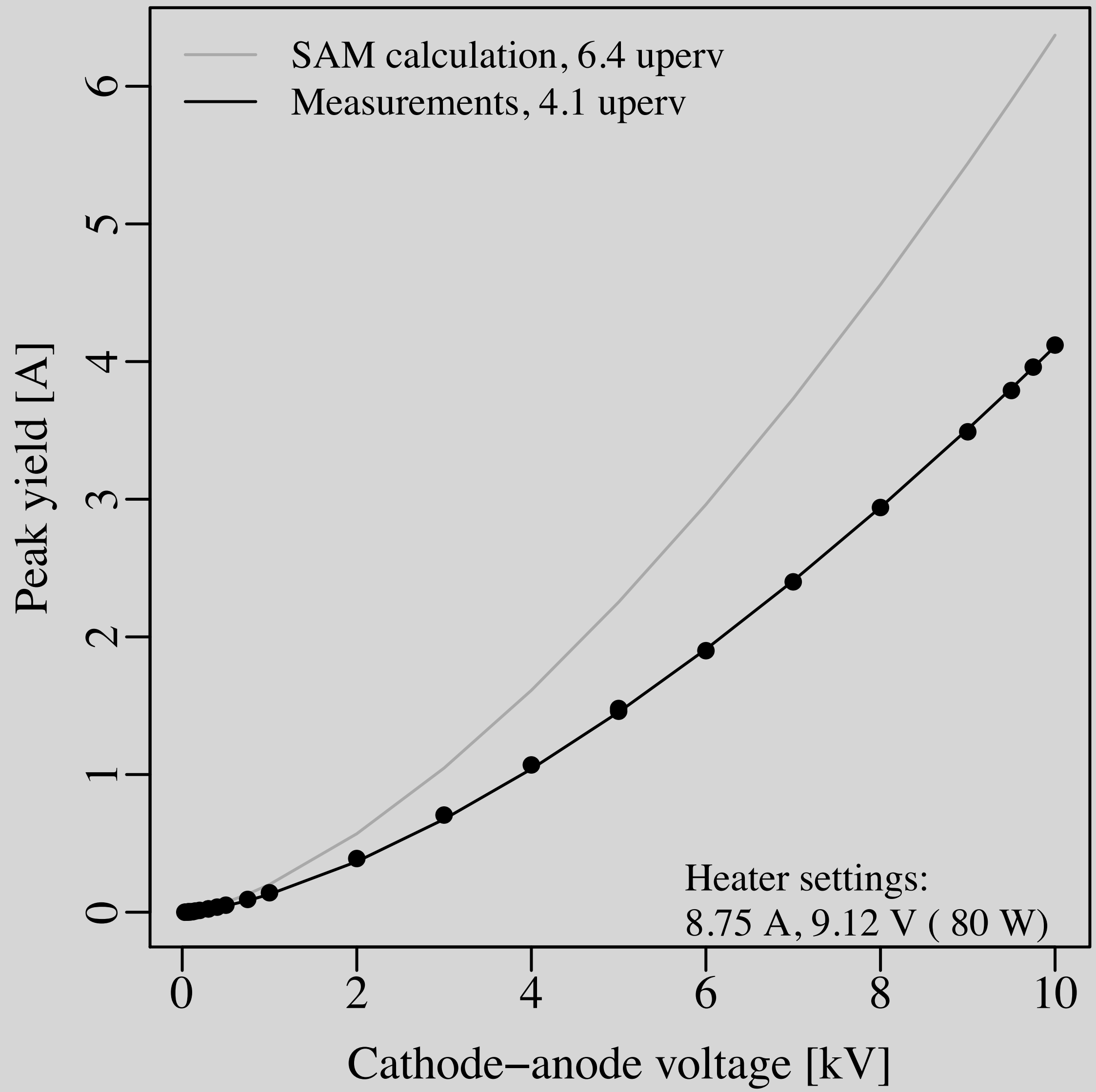


Reasonable power to reach operating temperature

25-mm hollow electron gun: pulse @ 8 kV, 2.85 A

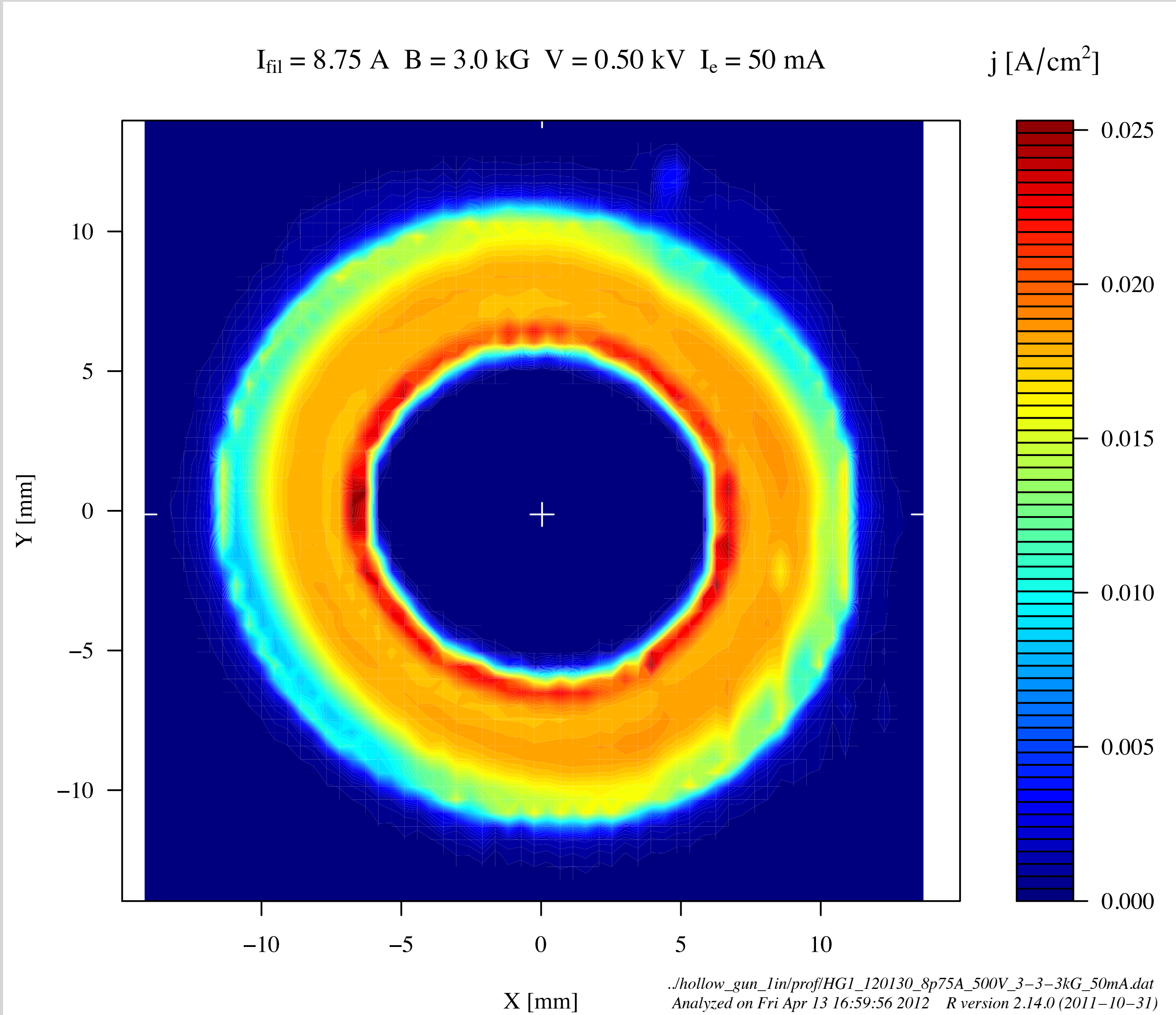


25-mm hollow electron gun: performance



Yield is 30% lower than calculated

25-mm hollow electron gun: measured profiles

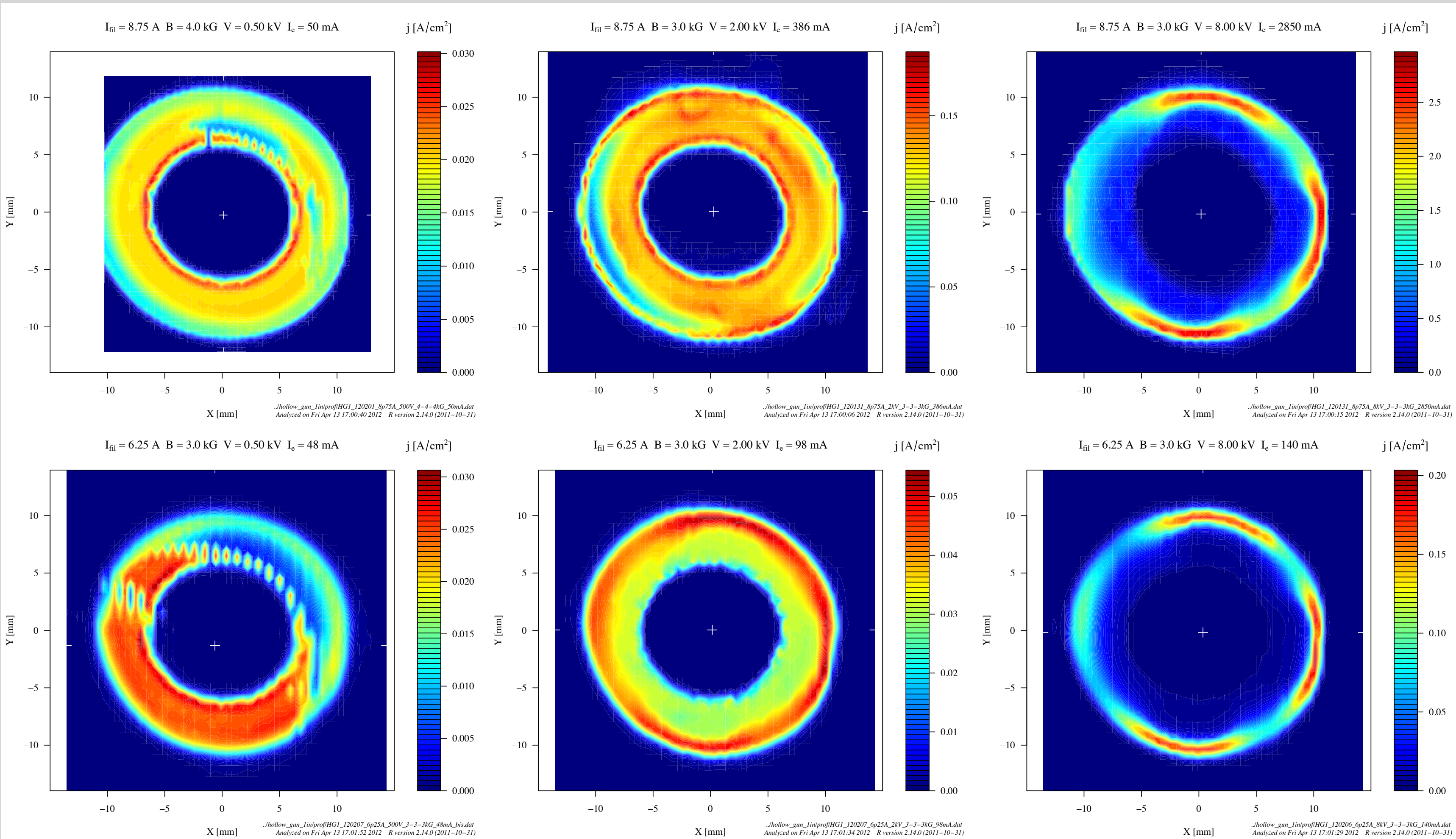


25-mm hollow electron gun: profile vs. voltage and current

0.5 kV	2 kV	8 kV
50 mA	386 mA	2850 mA

Hot (8.75 A)

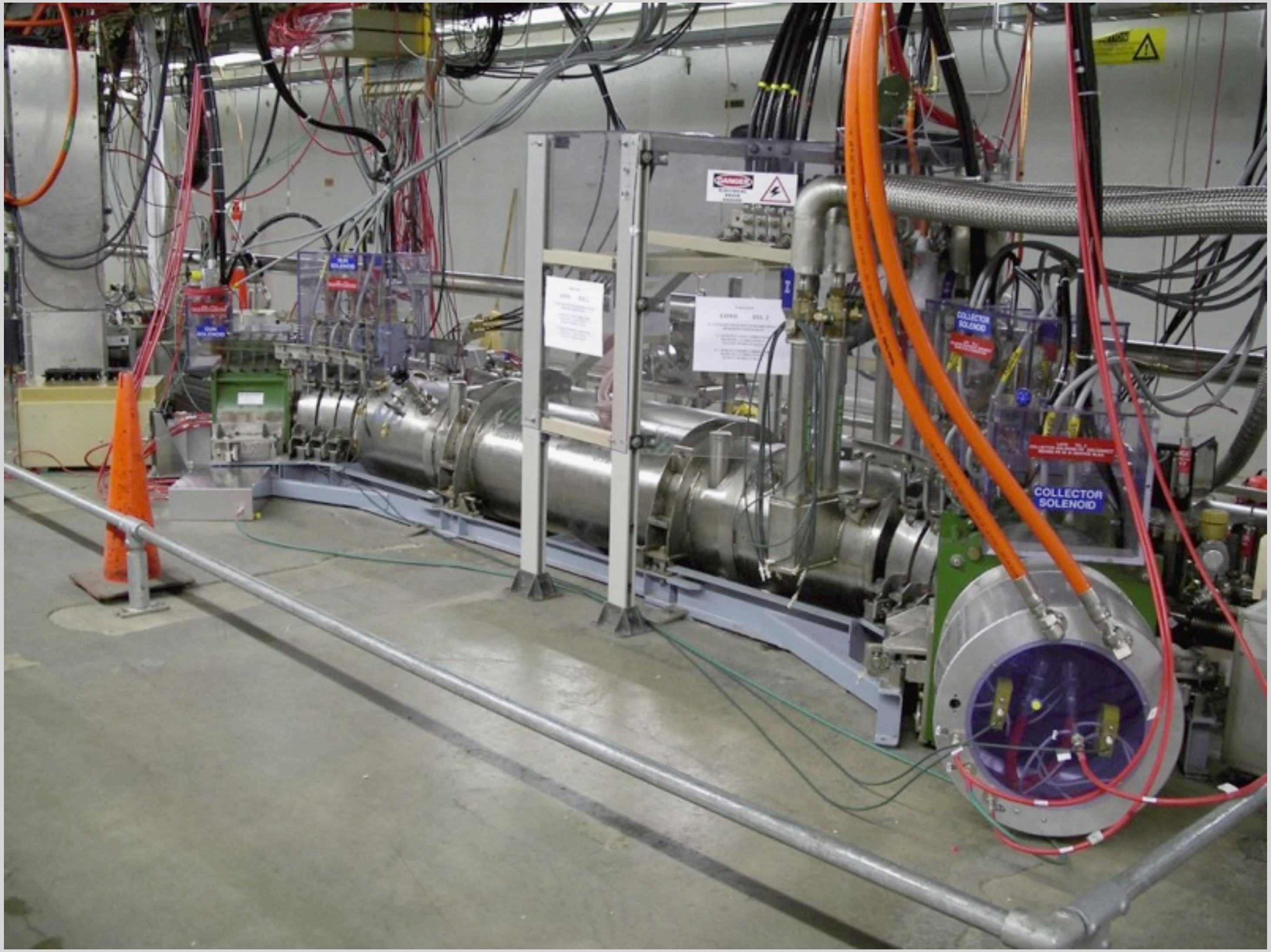
Cold (6.25 A)



48 mA	98 mA	140 mA

Profile depends mostly on voltage and not on current => mechanical imperfections

Tevatron electron lens hardware to CERN?



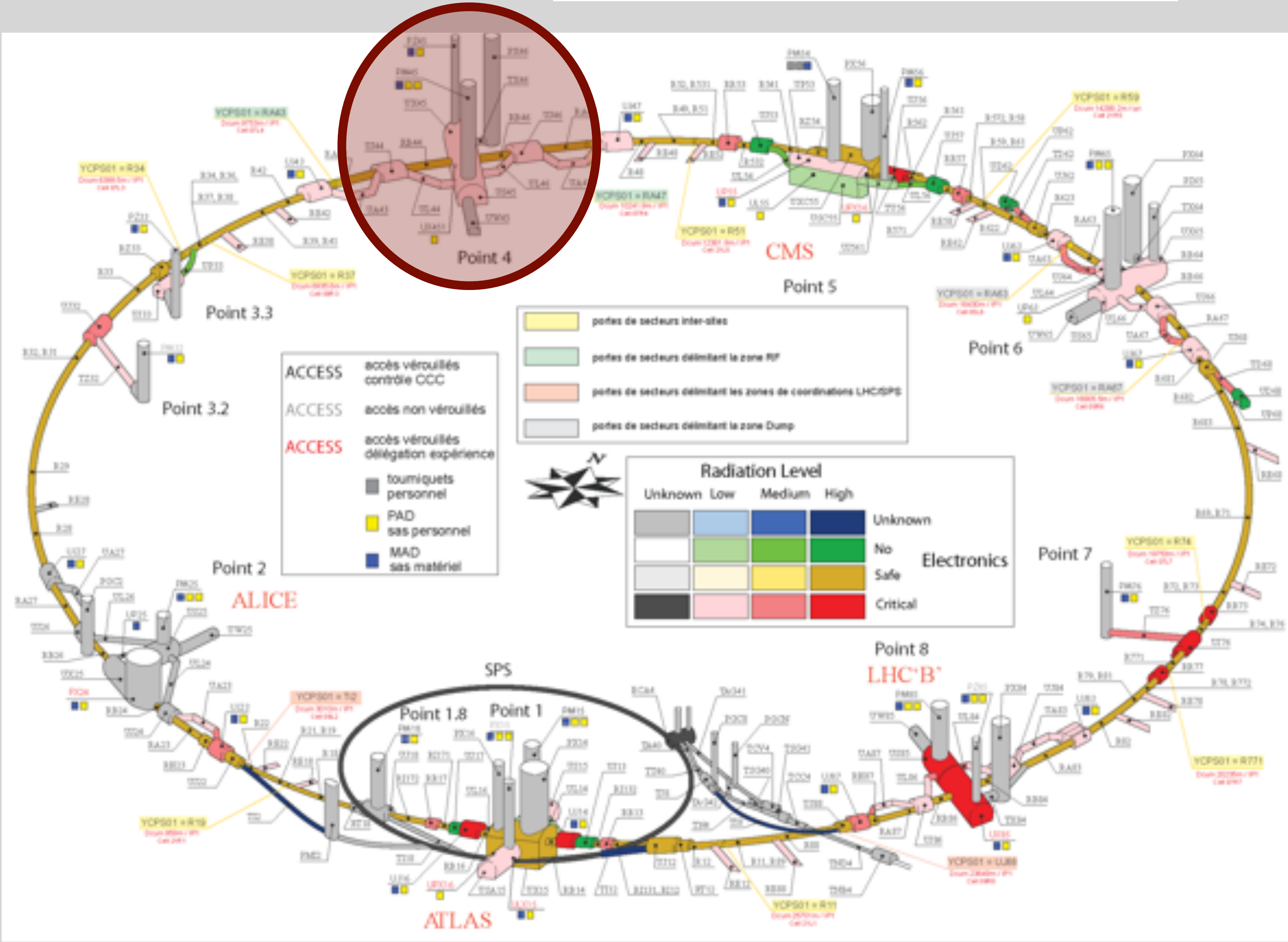
- TEL2 hardware is available, including power supplies
- Investigating its possible use at CERN with LHC Collimation Group

Application of hollow electron beam collimation at CERN

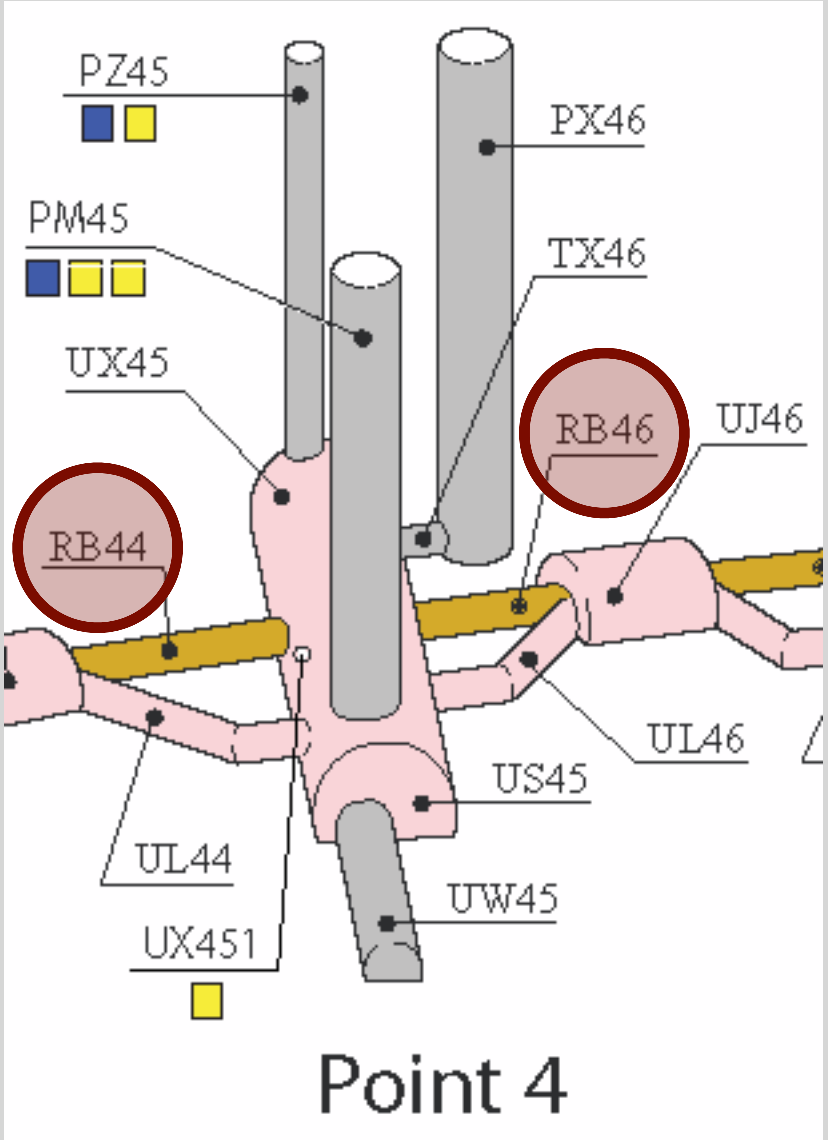
- Purpose:
  - study physics of hollow electron beam collimation in LHC
  - complement primary collimators
  - flexible halo control
- Practical considerations:
  - preparatory studies possible during dead time of accelerator complex (beam alignment, pulse synchronization)
  - can be operated parasitically (abort gap, few bunches, end of fill)
  - safe: can always be turned off
  - **potentially high physics payoff for relatively low cost and low risk**
- When and where?
  - LHC preferable over SPS (more interesting, better beam and diagnostics)
  - LS1 feasible from Fermilab's point of view

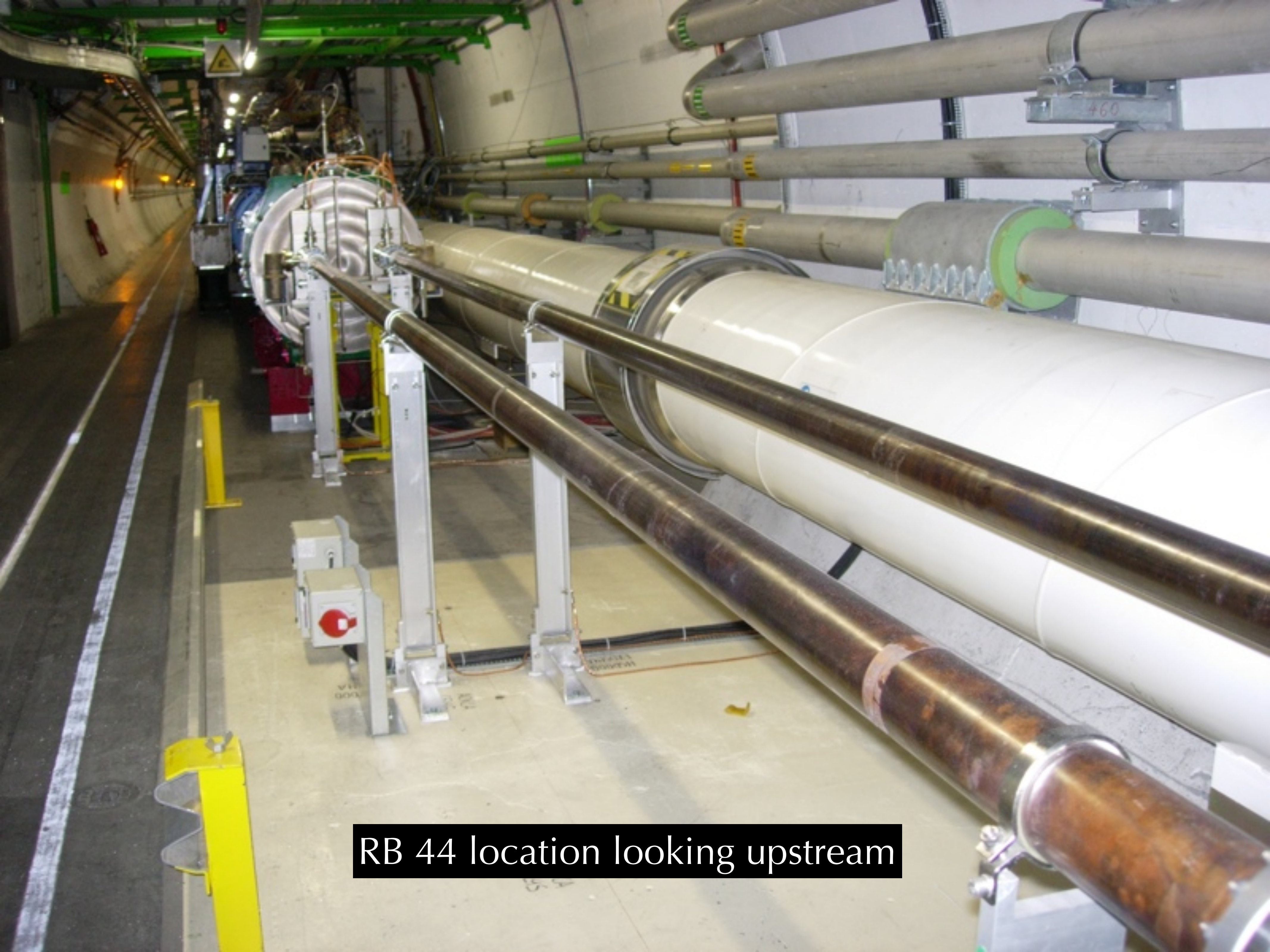
LHC IR4 candidate location

beam separation is large (42 cm)



Detail of IR4 in LHC

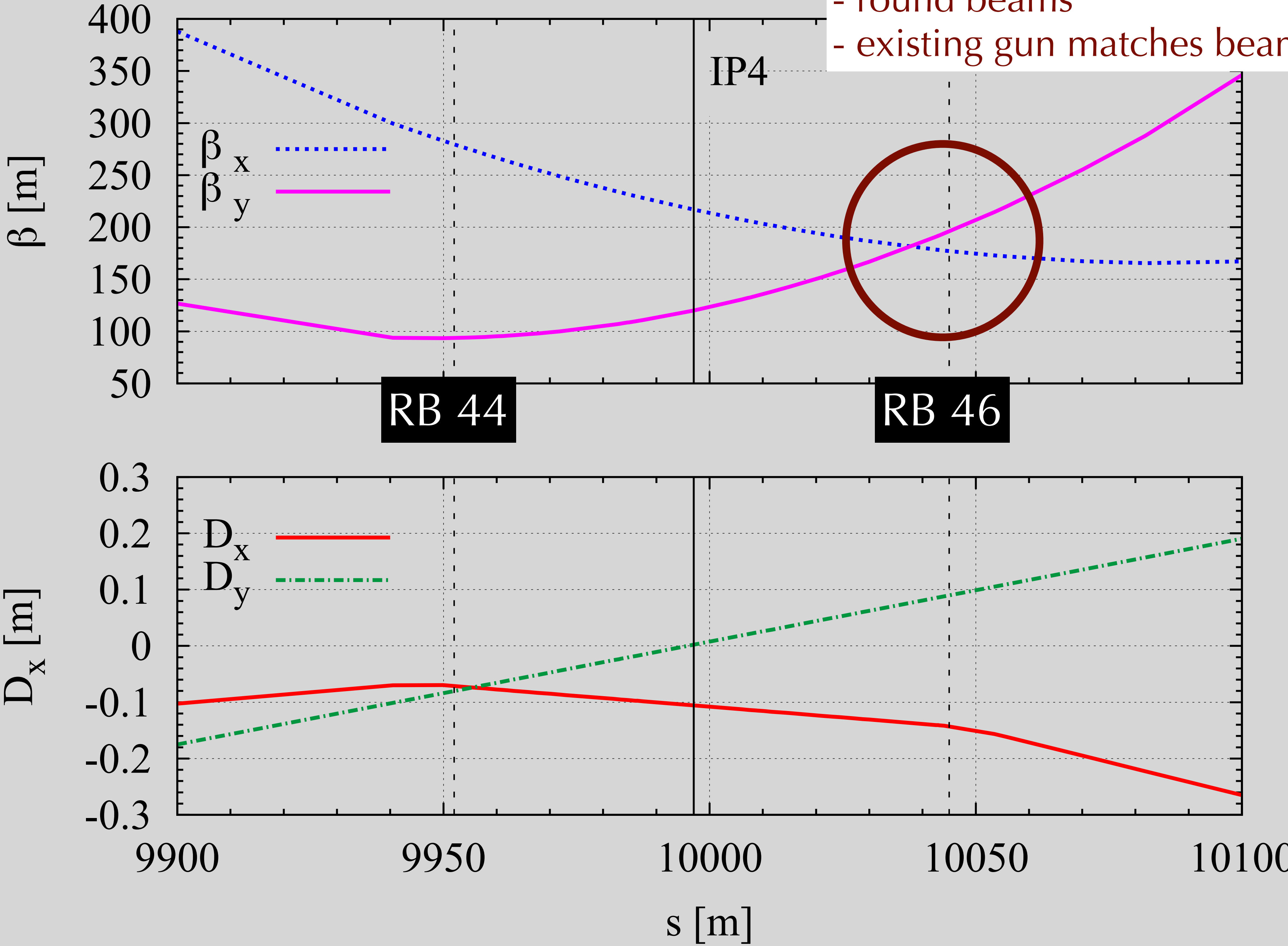




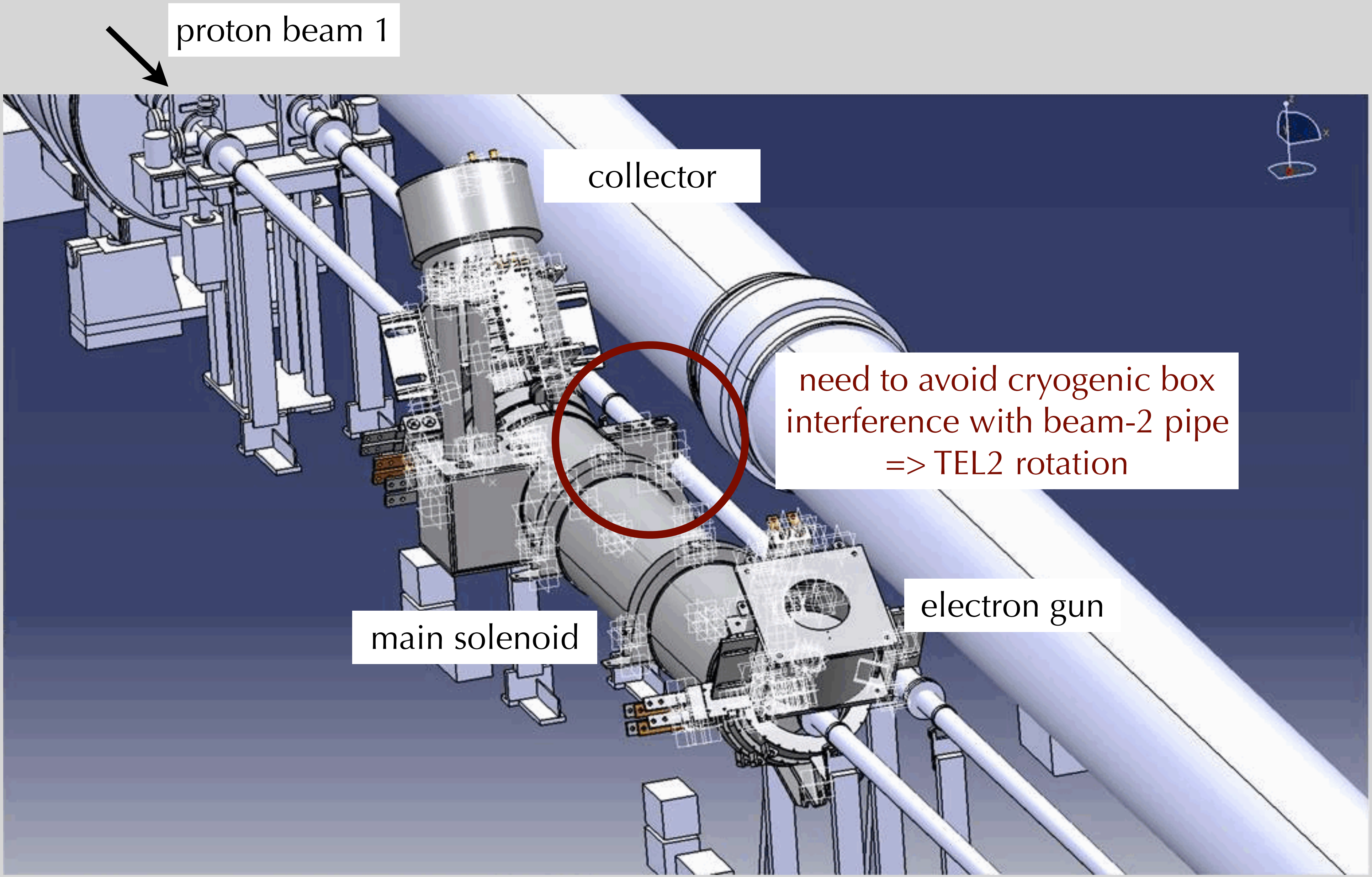
RB 44 location looking upstream

LHC IR4 beam-1 optics v6.503

preferred location:
- round beams
- existing gun matches beam size

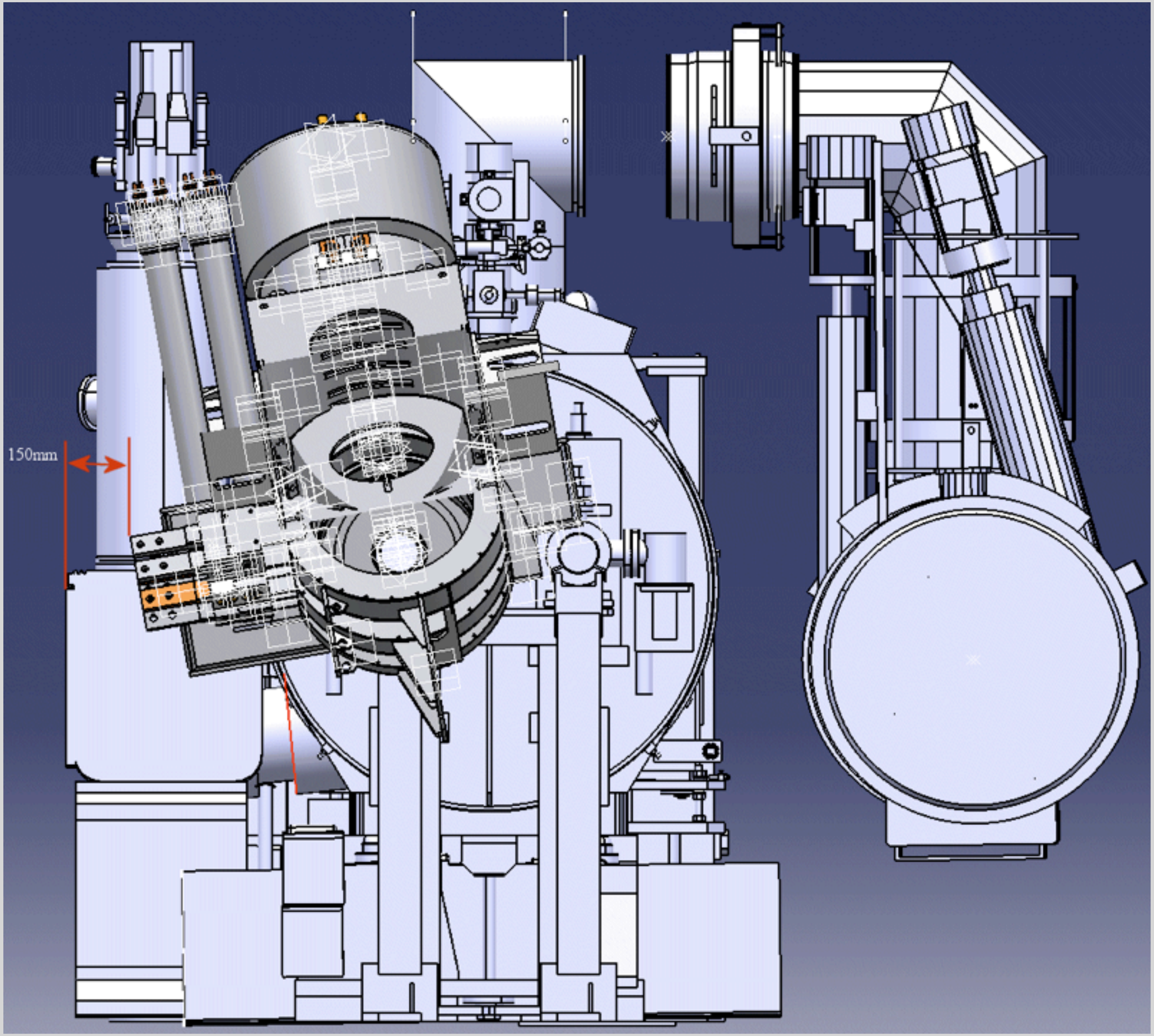


TEL2 integration study in LHC: IR4 / RB44 location



Thanks to Y. Muttoni and CERN integration group

TEL2 integration study in LHC: IR4 / RB44 location



TEL2 integration in LHC

- Physical space is tight, but mechanical integration seems feasible.
- No liquid N_2 available. Possible solutions: use high pressure helium (requires TEL2 tests) or reduce pressure. Substantial cryogenic work may be required.
- Some preparatory work can be done at Fermilab:
  - vacuum and cryogenic checks
  - residual radioactivity
  - hardware documentation

Further information

- **Papers**
  - PAC 01, p. 3630 [TEL magnets and cryogenics]
  - PRL **99**, 244801 (2007) [beam-beam compensation]
  - PRSTAB **11**, 103501 (2008) [TEL design and operation]
  - IPAC 10, TUPEB076 [hollow gun design and performance]
  - PRL **107**, 084802 (2011) [hollow beam collimation]
  - IPAC11, p. 1939 [hollow beam collimation]
  - arXiv:1110.0144 [hollow beam collimation]
- **Web pages**
  - https://cdcvs.fnal.gov/redmine/projects/elens/wiki [new e-lens wiki]
  - http://www-bd.fnal.gov/lug/tev33/ebeam_comp [original e-lens pages]

Summary

- **Hollow electron beams open up new options for beam scraping in high-intensity storage rings and colliders**
- Tevatron experiments provide **experimental foundation**
- Numerical simulations
  - understanding of removal rates vs. e-lens parameters in Tevatron
  - effects in LHC should be observable with existing TEL2 gun
  - incorporate e-lens model in SixTrack, which includes LHC collimation system
- 25-mm prototype electron gun
  - tested heating system and high-voltage rating
  - needs more work to reach design performance (yield / profile)
- Integration studies of TEL2 in LHC
  - existing hardware matches LHC beam
  - mechanically feasible
  - may require substantial cryogenic work

Thank you!

Backup

The conventional multi-stage collimation system

Goals of collimation:

- reduce beam halo
- direct losses towards absorbers

Implementations:

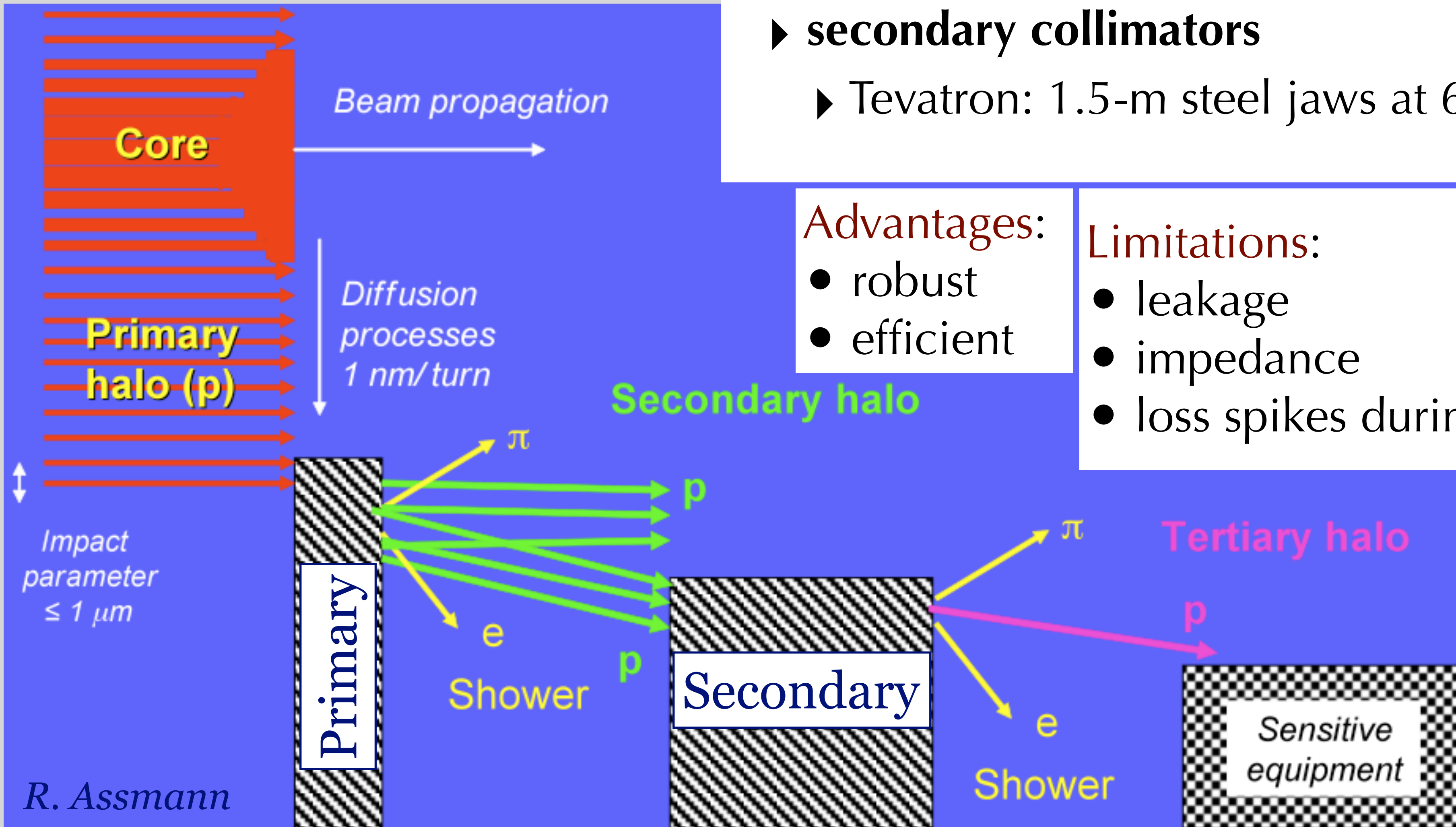
- **primary collimators**
  - Tevatron: 5-mm W at 5σ
  - LHC: 0.6-m carbon jaws at 6σ
- **secondary collimators**
  - Tevatron: 1.5-m steel jaws at 6σ

Advantages:

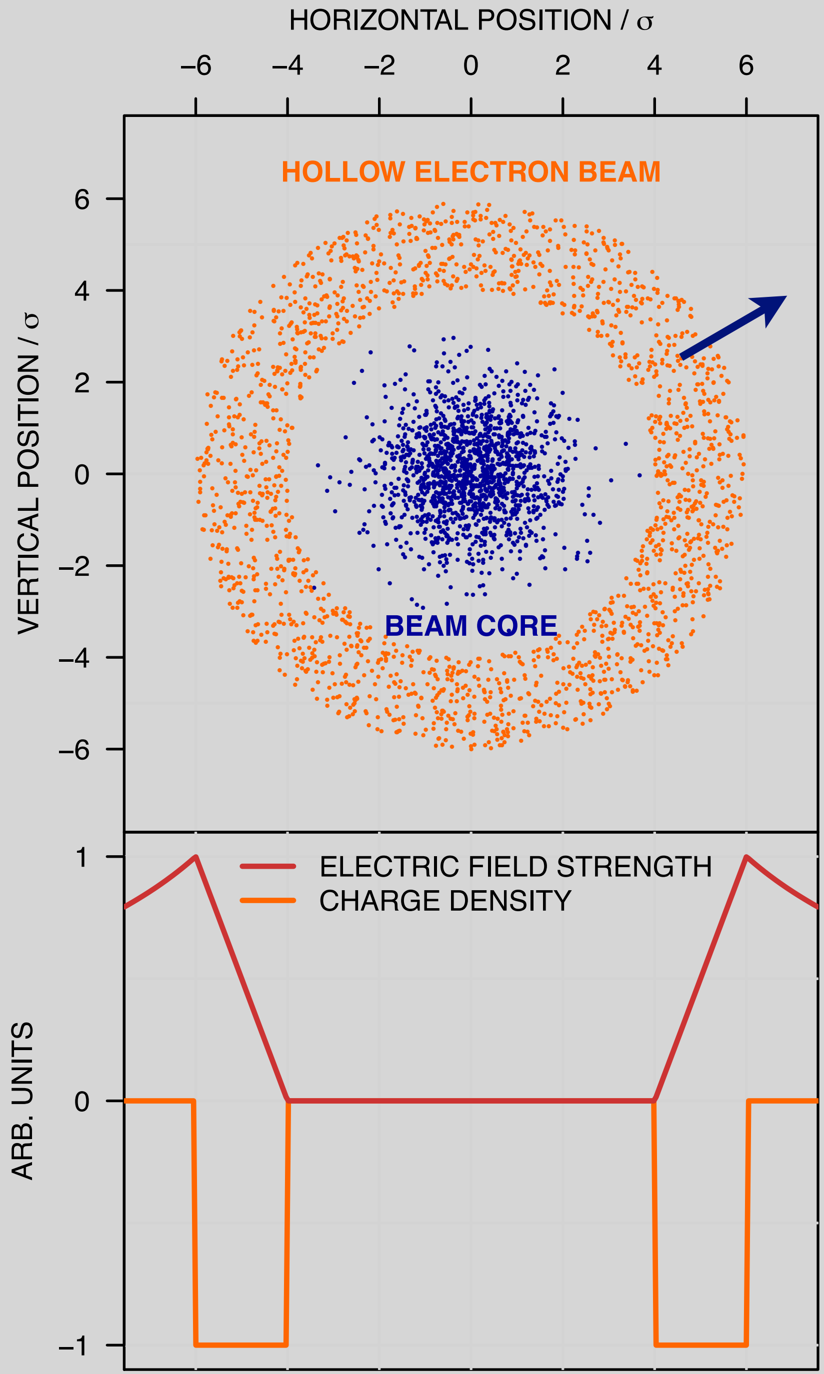
- robust
- efficient

Limitations:

- leakage
- impedance
- loss spikes during setup



Concept of hollow electron beam collimator (HEBC)



Halo experiences nonlinear transverse kicks:

$$\theta_r = \frac{2\, I_r\, L\, (1 \pm \beta_e \beta_p)}{r\, \beta_e\, \beta_p\, c^2\, (B\rho)_p} \left(\frac{1}{4\pi\epsilon_0} \right)$$

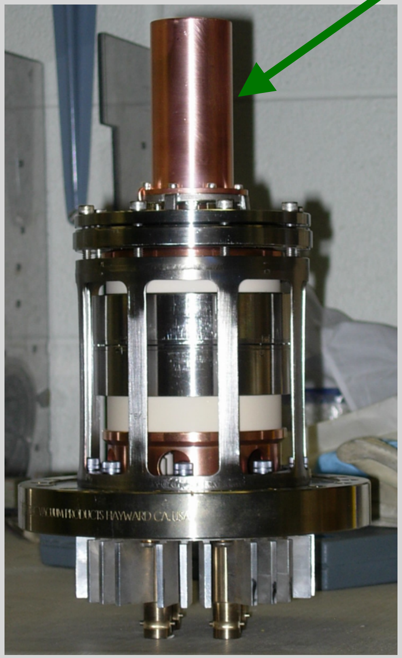
About **0.2 µrad**
in TEL2 at 980 GeV

For comparison:
multiple scattering
in Tevatron collimators
$\theta_{\rm rms} = 17\ \mu{\rm rad}$

Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08

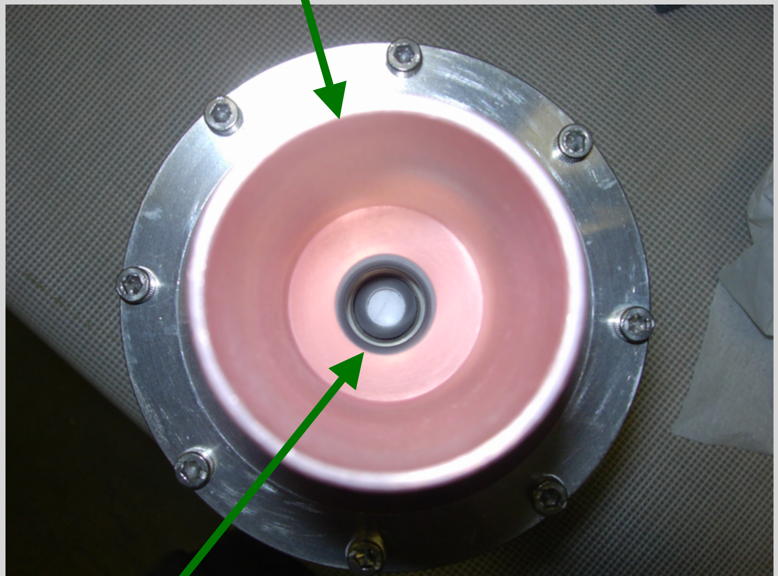
The 15-mm hollow electron gun

side view



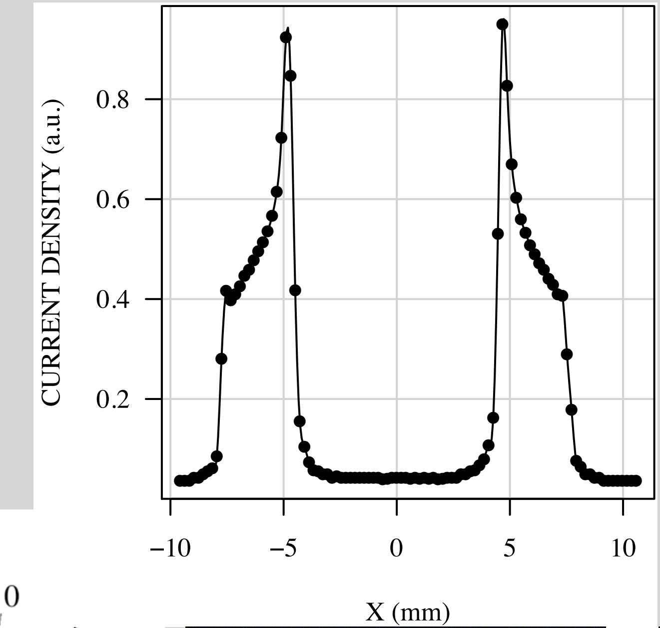
Copper anode

top view

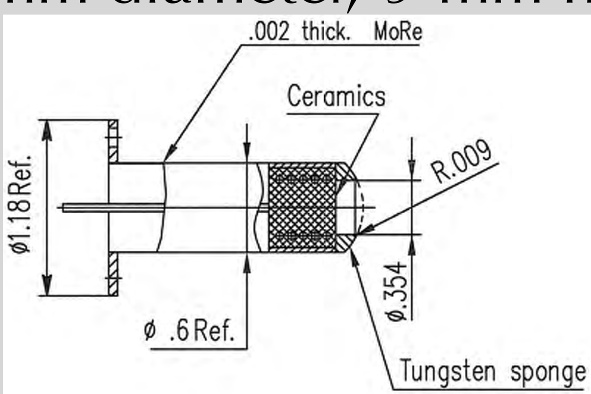


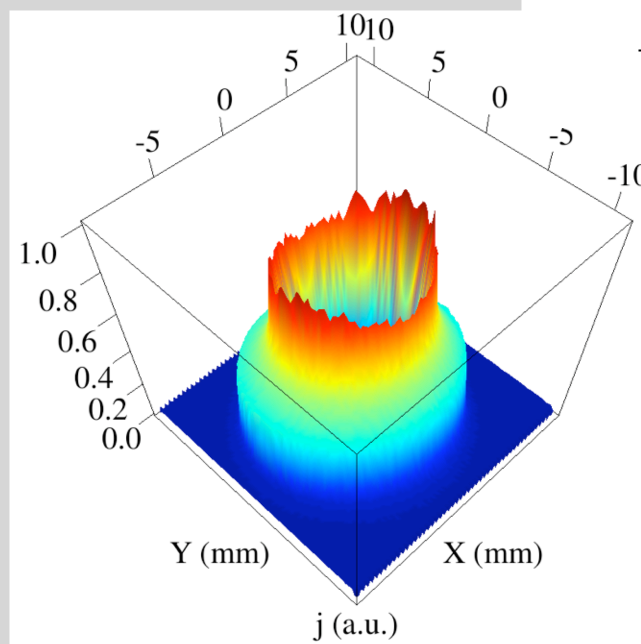
Yield: **1.1 A** at 4.8 kV

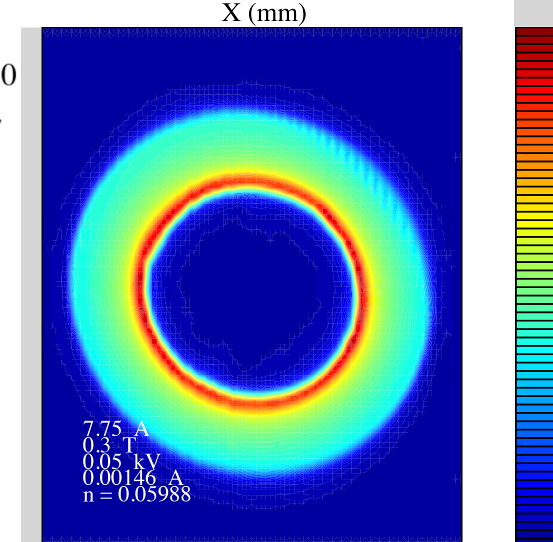
Profile measurements



Tungsten dispenser cathode
with convex surface
15-mm diameter, 9-mm hole







A good complement to a two-stage system for high intensities?

- Can be close to or even overlap with the main beam
  - no material damage
  - tunable strength (“variable thickness”)
- Works as “soft scraper” by enhancing diffusion
- Low impedance
- Resonant excitation is possible (pulsed e-beam)
- No ion breakup
- Position control by magnetic fields (no motors or bellows)
- Established electron-cooling / electron-lens technology
- Critical beam alignment
- Control of hollow beam profile
- Beam stability at high intensity
- Cost

First results published in PRL

PRL **107,** 084802 (2011) PHYSICAL REVIEW LETTERS week ending 19 AUGUST 2011

Collimation with Hollow Electron Beams

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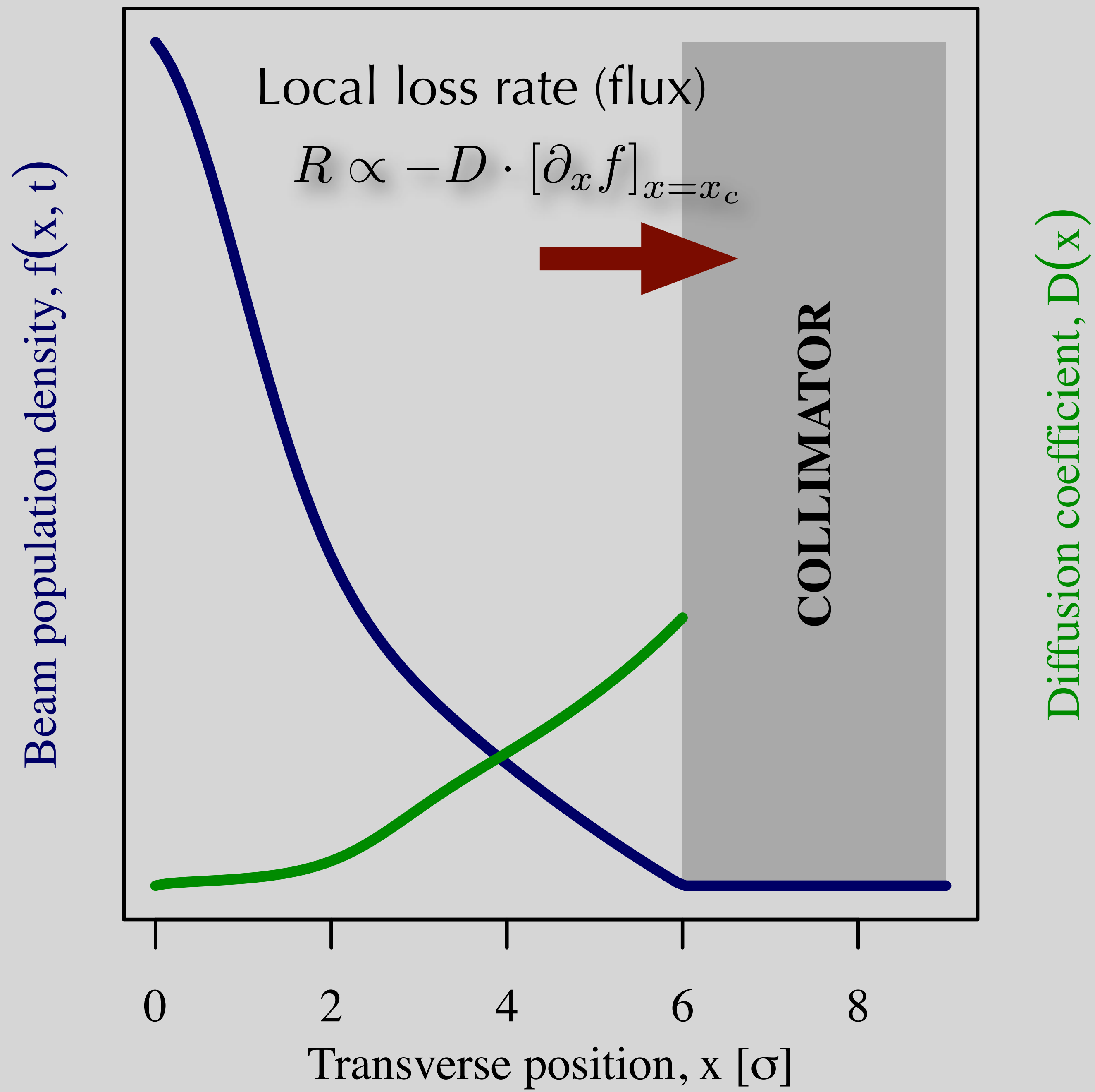
(Received 16 May 2011; published 17 August 2011)

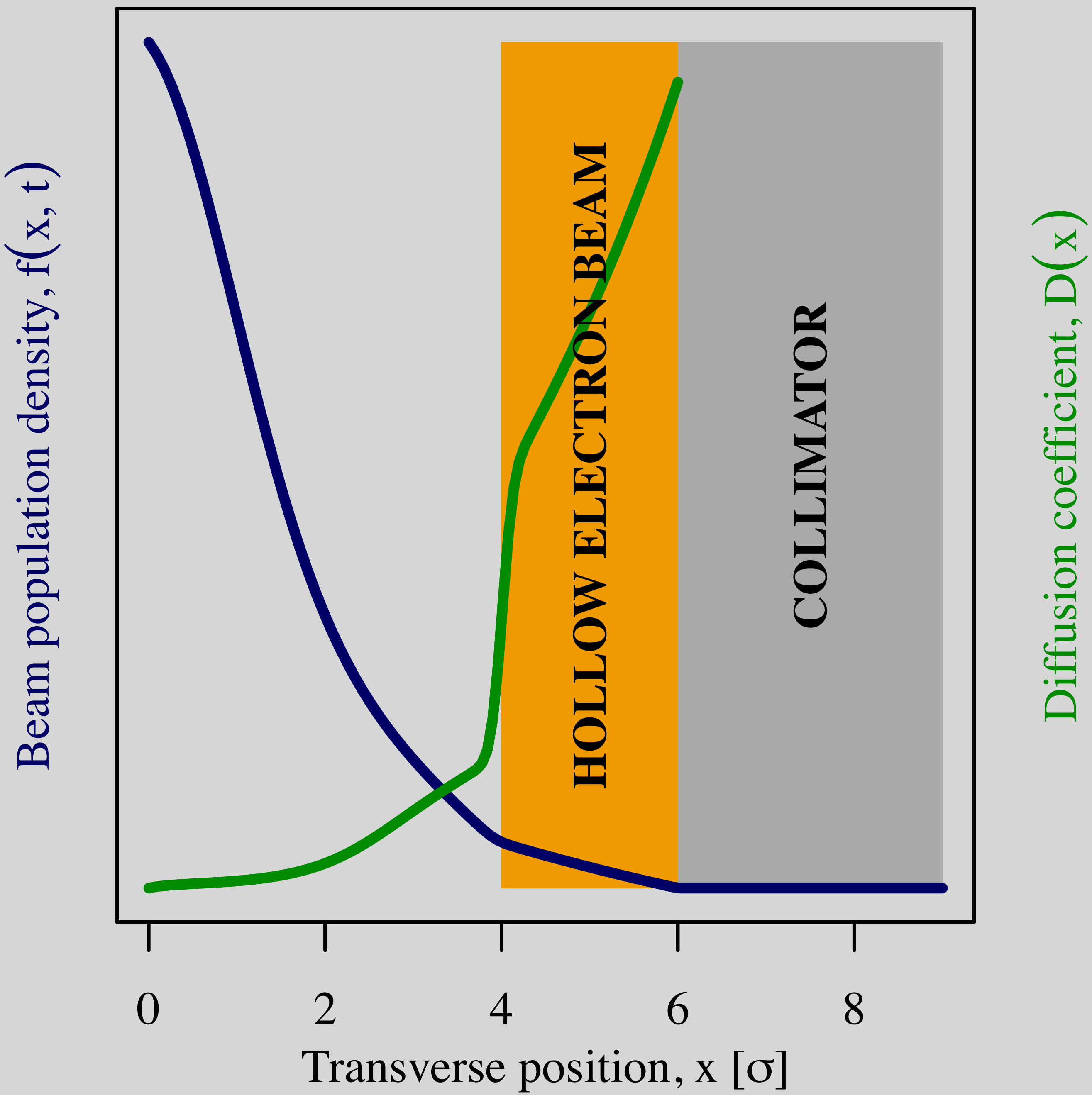
A novel concept of controlled halo removal for intense high-energy beams in storage rings and colliders is presented. It is based on the interaction of the circulating beam with a 5-keV, magnetically confined, pulsed hollow electron beam in a 2-m-long section of the ring. The electrons enclose the circulating beam, kicking halo particles transversely and leaving the beam core unperturbed. By acting as a tunable diffusion enhancer and not as a hard aperture limitation, the hollow electron beam collimator extends conventional collimation systems beyond the intensity limits imposed by tolerable losses. The concept was tested experimentally at the Fermilab Tevatron proton-antiproton collider. The first results on the collimation of 980-GeV antiprotons are presented.

DOI: 10.1103/PhysRevLett.107.084802 PACS numbers: 29.27.−a, 41.85.Si

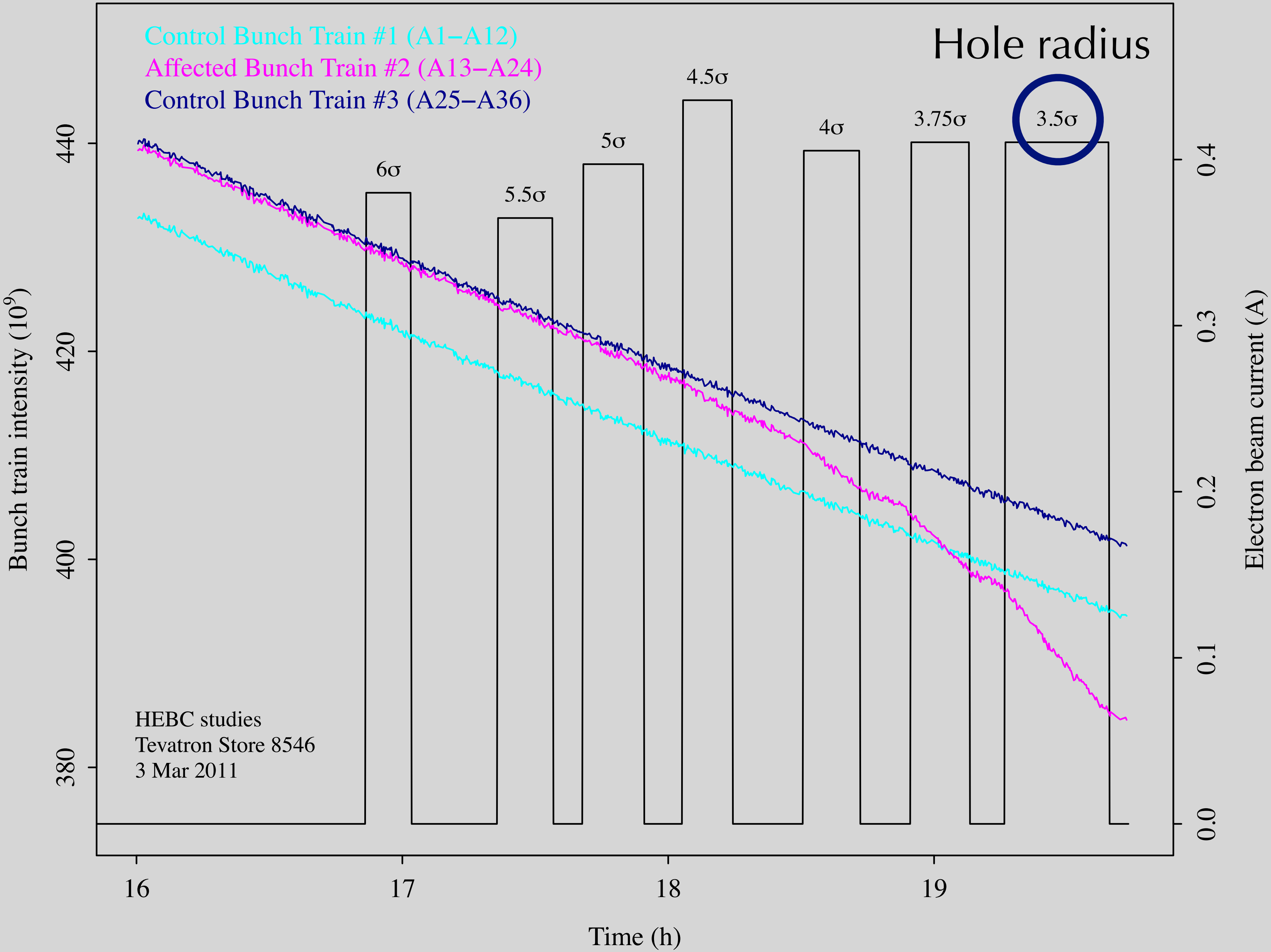
1-dimensional diffusion cartoon of collimation



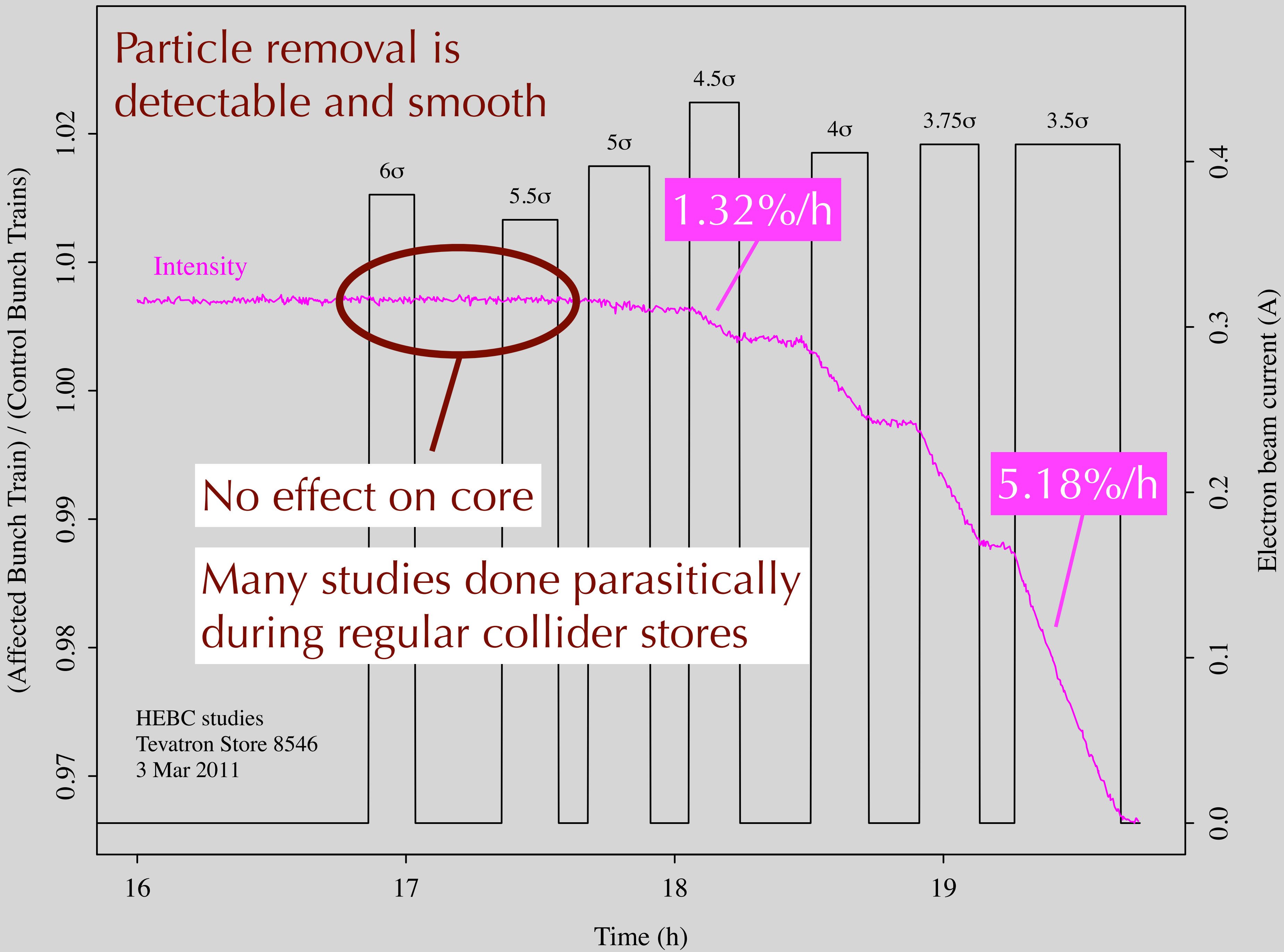
1-dimensional diffusion cartoon with hollow electron beam



Electrons acting on 1 antiproton bunch train (#2, A13-A24)



Removal rate: affected bunch train relative to other 2 trains



Is the core affected? Are particles removed from the halo?

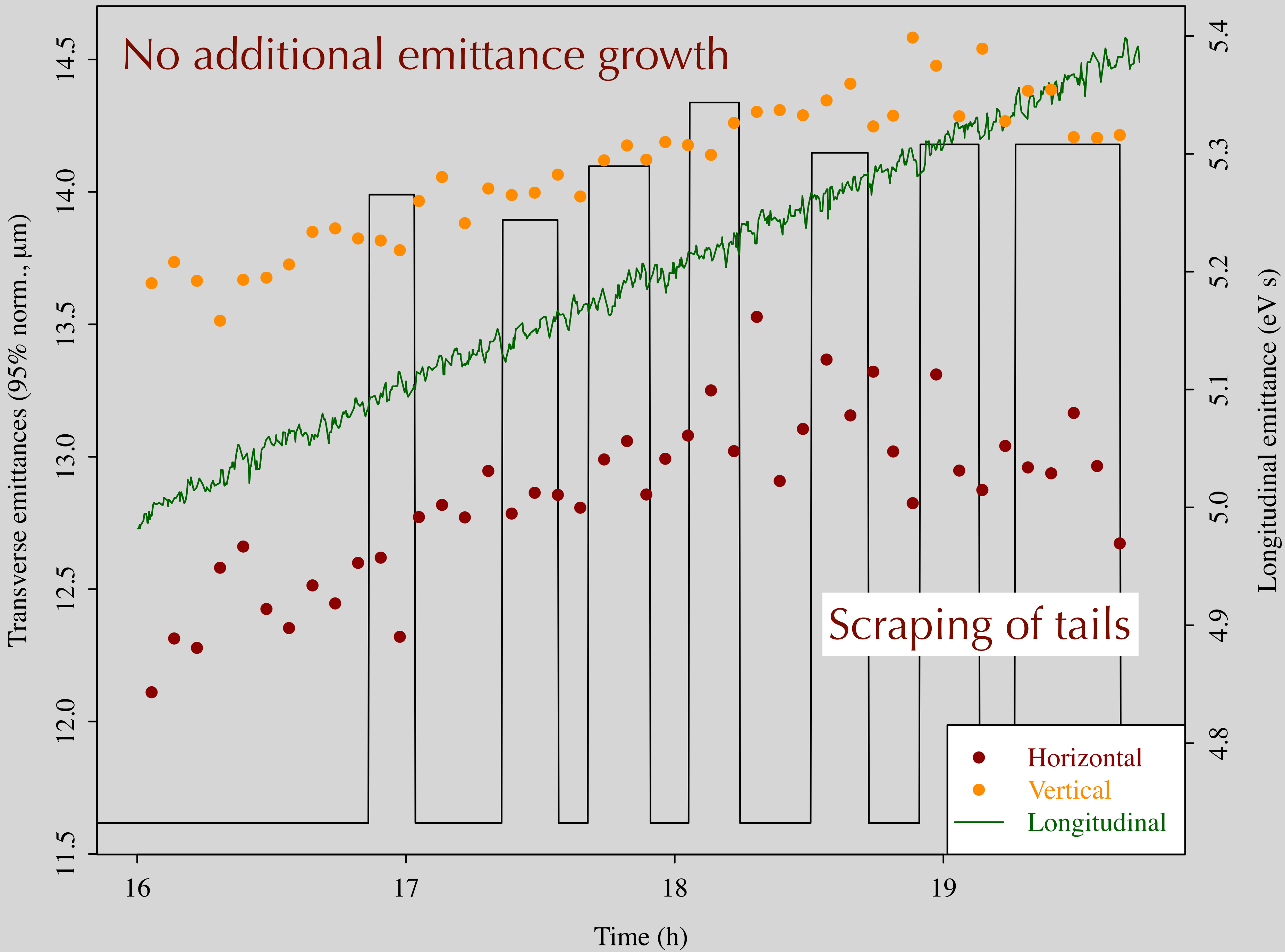
Several strategies:

- **No removal** when e-beam is shadowed by collimators (previous slide)
- Check **emittance** evolution
- Compare **intensity** and **luminosity** change when scraping antiprotons:

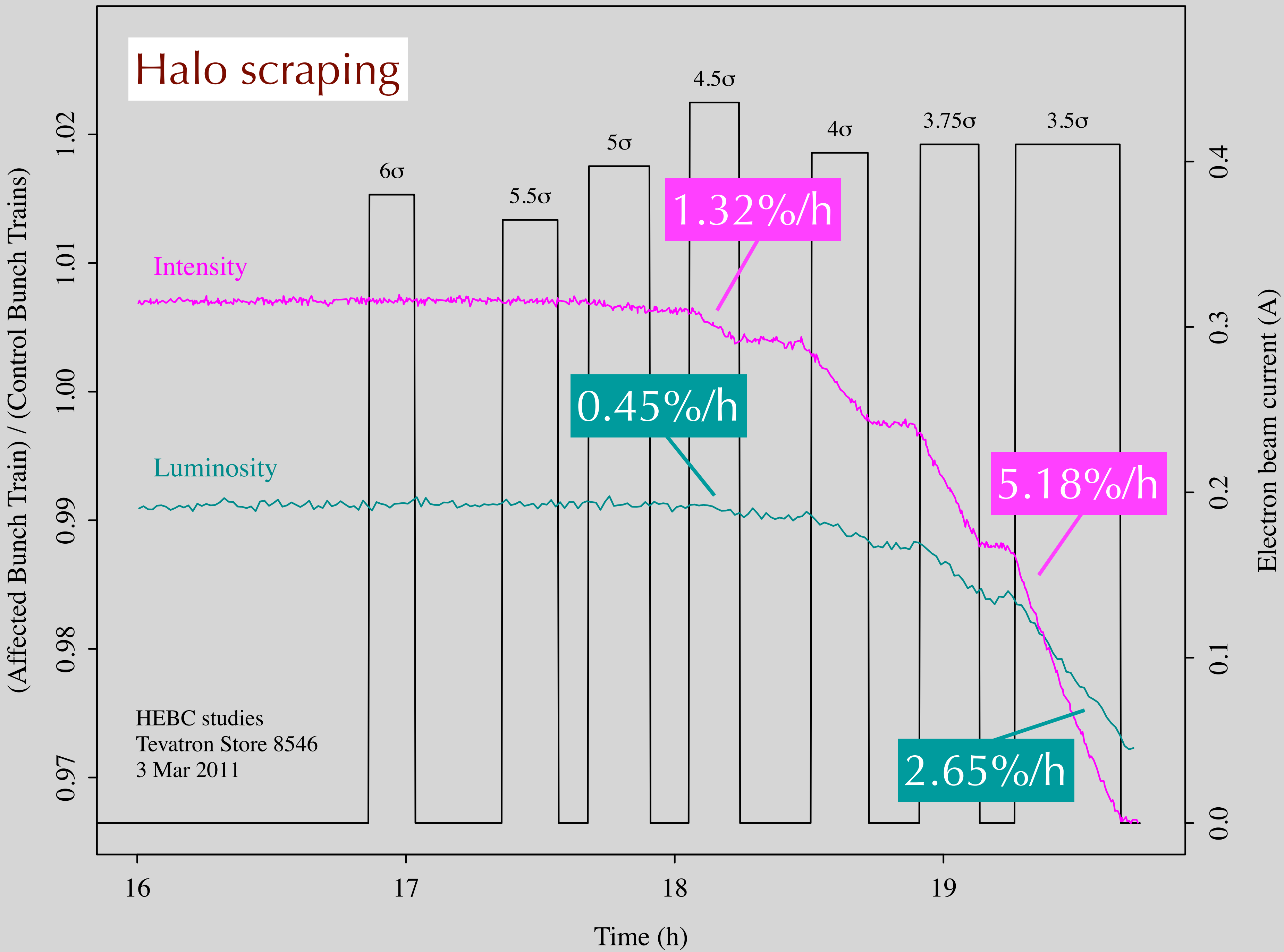
$$\mathcal{L} = \left(\frac{f_{\mathrm{rev}} N_b}{4\pi} \right) \frac{N_p N_a}{\sigma^2} \qquad\qquad \frac{\Delta \mathcal{L}}{\mathcal{L}} = \frac{\Delta N_p}{N_p} + \frac{\Delta N_a}{N_a} - 2\frac{\Delta \sigma}{\sigma}$$

  - same fractional variation if other factors are constant
  - luminosity decreases more if there is emittance growth or proton loss
  - luminosity decreases less if removing halo particles (smaller relative contribution to luminosity)
- **Removal rate** vs. amplitude (collimator scan, steady state)
- **Diffusion rate** vs. amplitude (collimator scan, time evolution of losses)

Emittances of affected bunch train

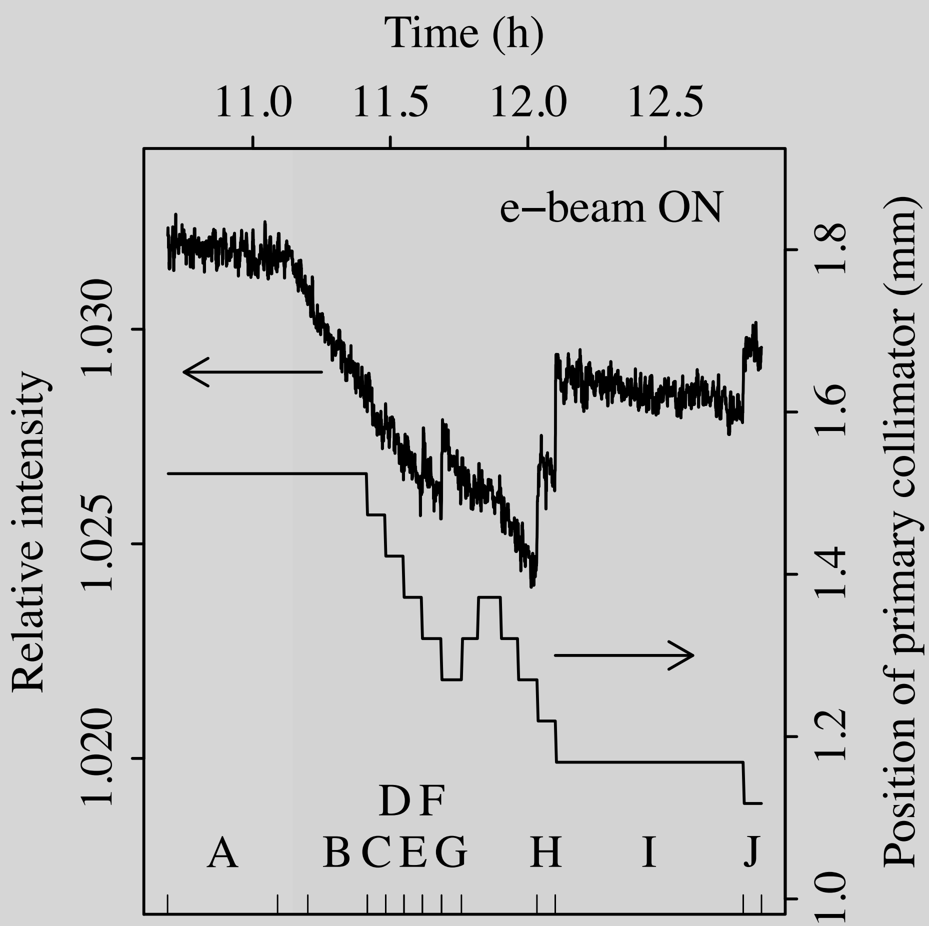


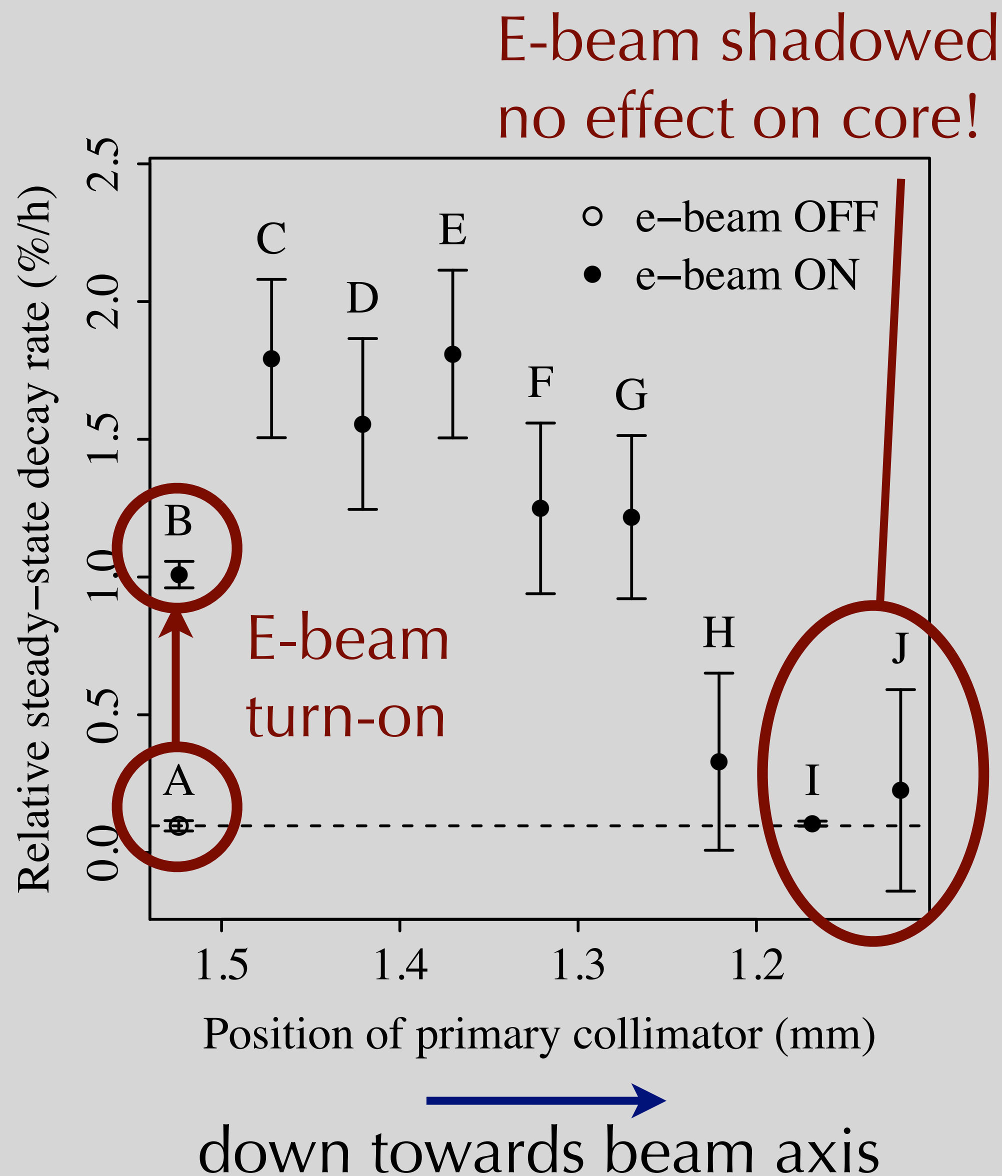
Luminosity of affected bunch train relative to other 2 trains



Removal rate vs. amplitude from collimator scan

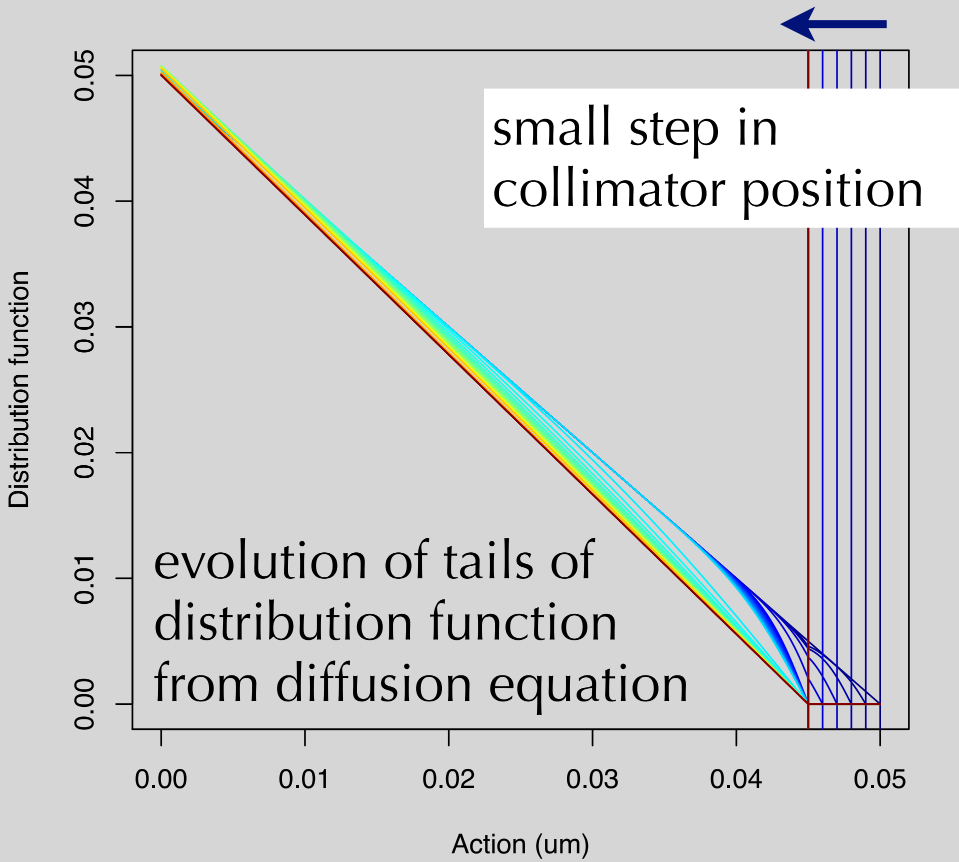
Electrons (0.15 A) on pbar train #2, 3.5σ hole (1.3 mm at collimator)
Vertical scan of primary collimator (others retracted)

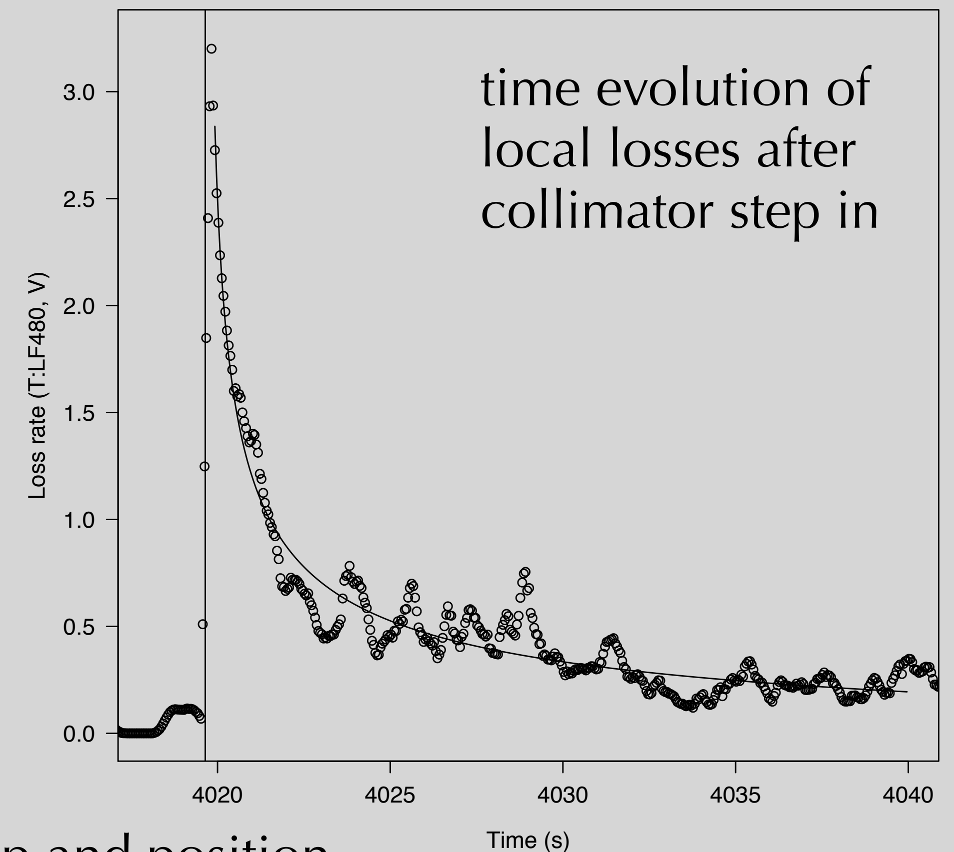




Diffusion rate vs. amplitude from collimator scans

Mess and Seidel, NIM A **351**, 279 (1994)





collimator step and position

observed loss rate

background

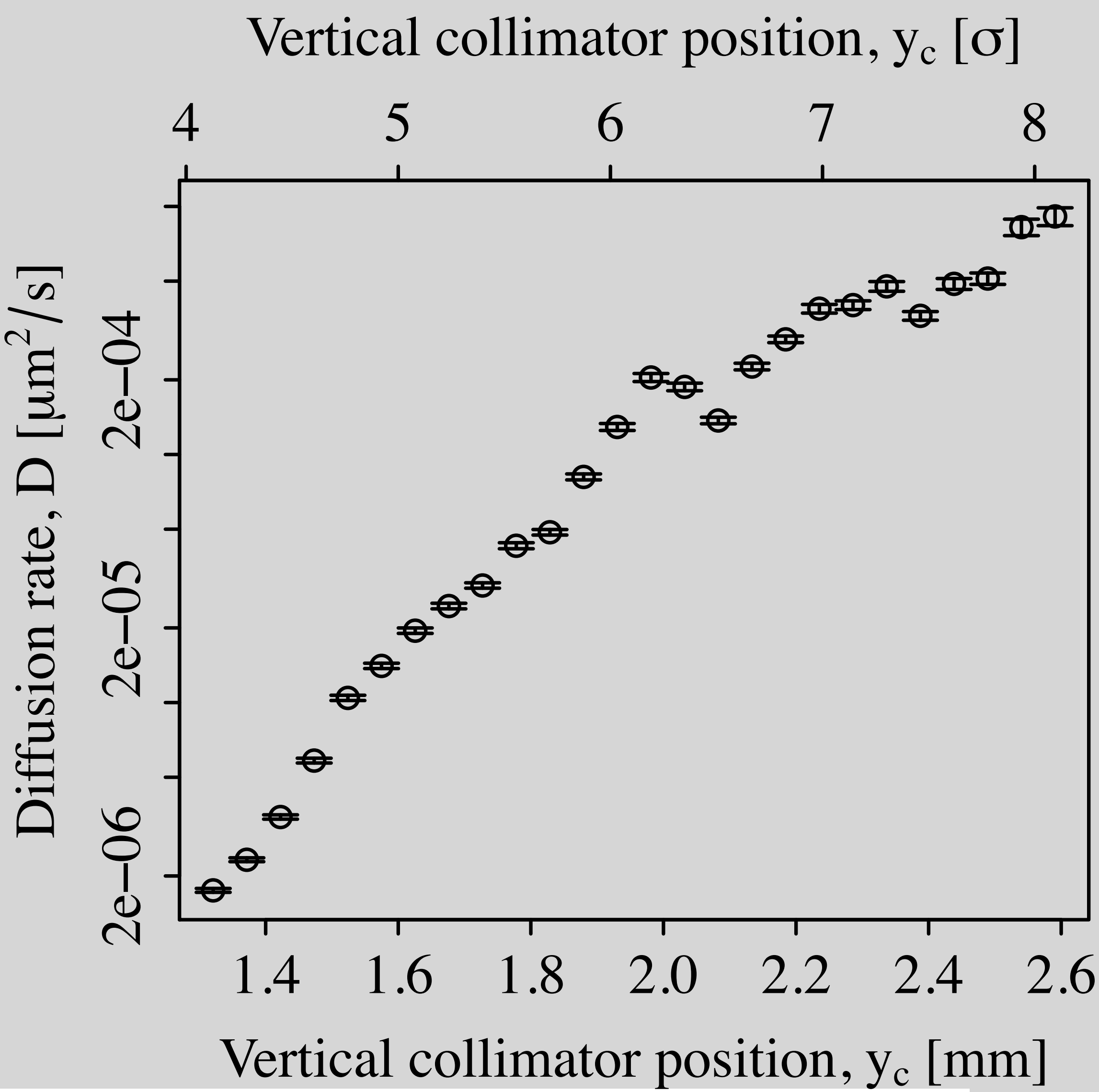
$$L(t) = a_1 \left\{ 1 + \frac{|\Delta x_c| / x_c}{\sqrt{\pi R (t - t_0)}} \right\} + a_0$$

normalization (intensity, efficiency, ...)

parameter related to diffusion rate

$$D = R \cdot x_c^4 / \beta_c^2$$

Diffusion rate vs. amplitude - preliminary



- First measurement of diffusion rates in Tevatron
- $D \sim J^{4.5}$

➡ see Stancari et al., IPAC11, TUPZ033
➡ arXiv:1108:5010

New gated antiproton loss monitors

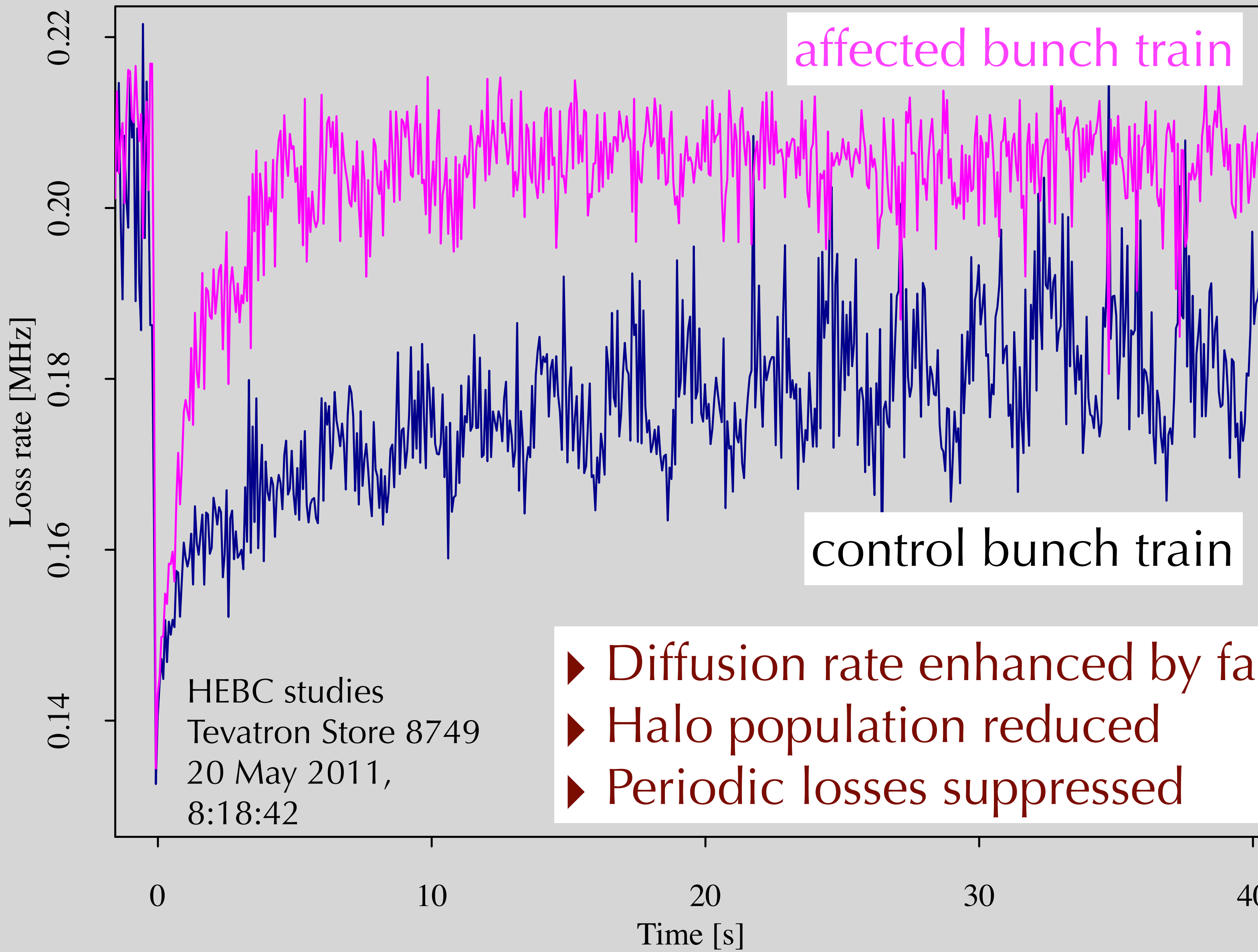
- Scintillator paddles installed near F49 antiproton absorber (Mar '11)
- Gated to individual bunch trains
- Recorded at 15 Hz

For simultaneous measurements of **diffusion rates**, **collimation efficiency**, and **loss spikes** on affected and control bunch trains at maximum electron currents

New gated loss monitors during collimator scan

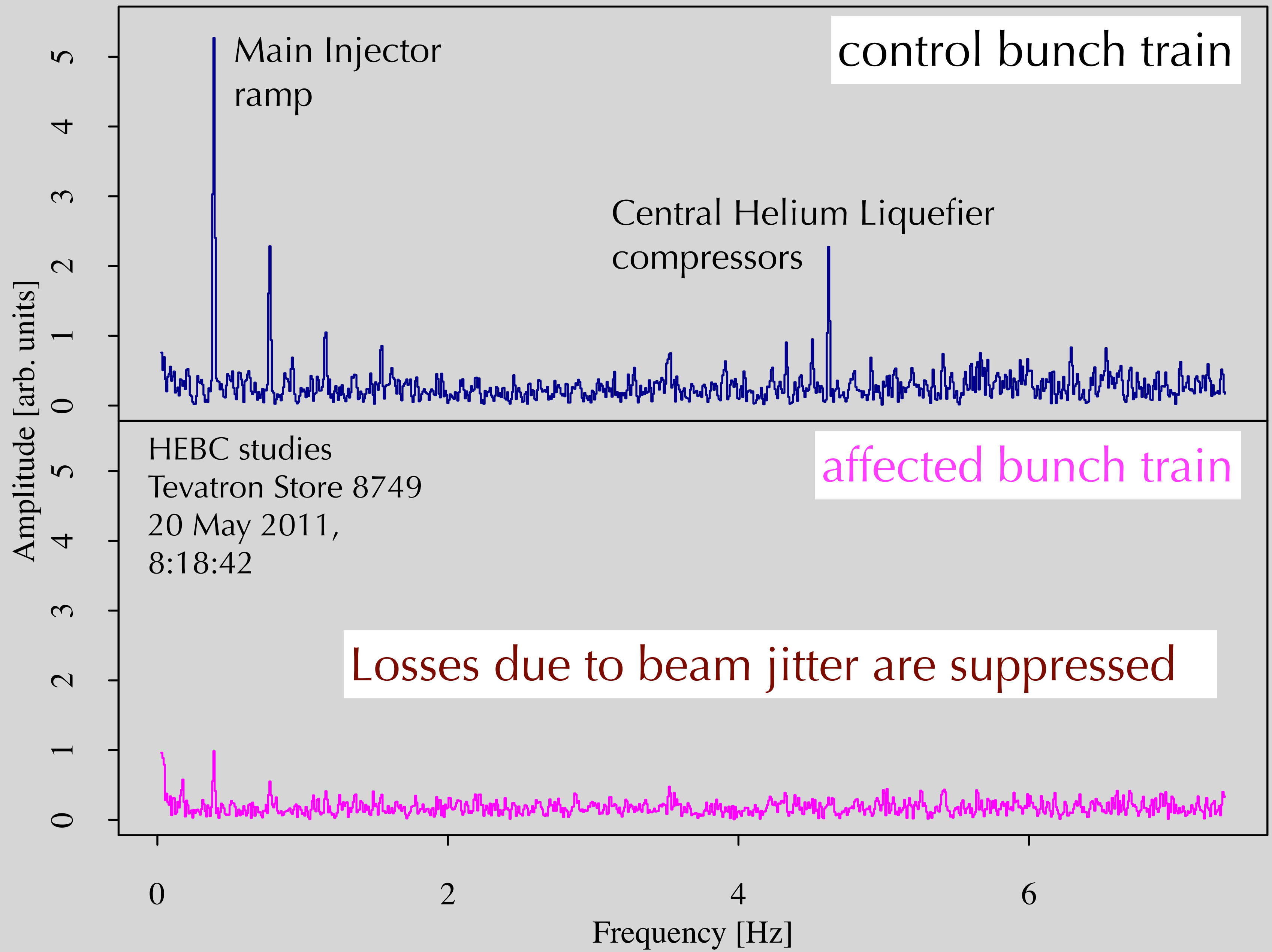
Electrons (0.9 A) on pbar train #2, 4.25σ hole

Example of **vertical collimator step out**, 50 μm

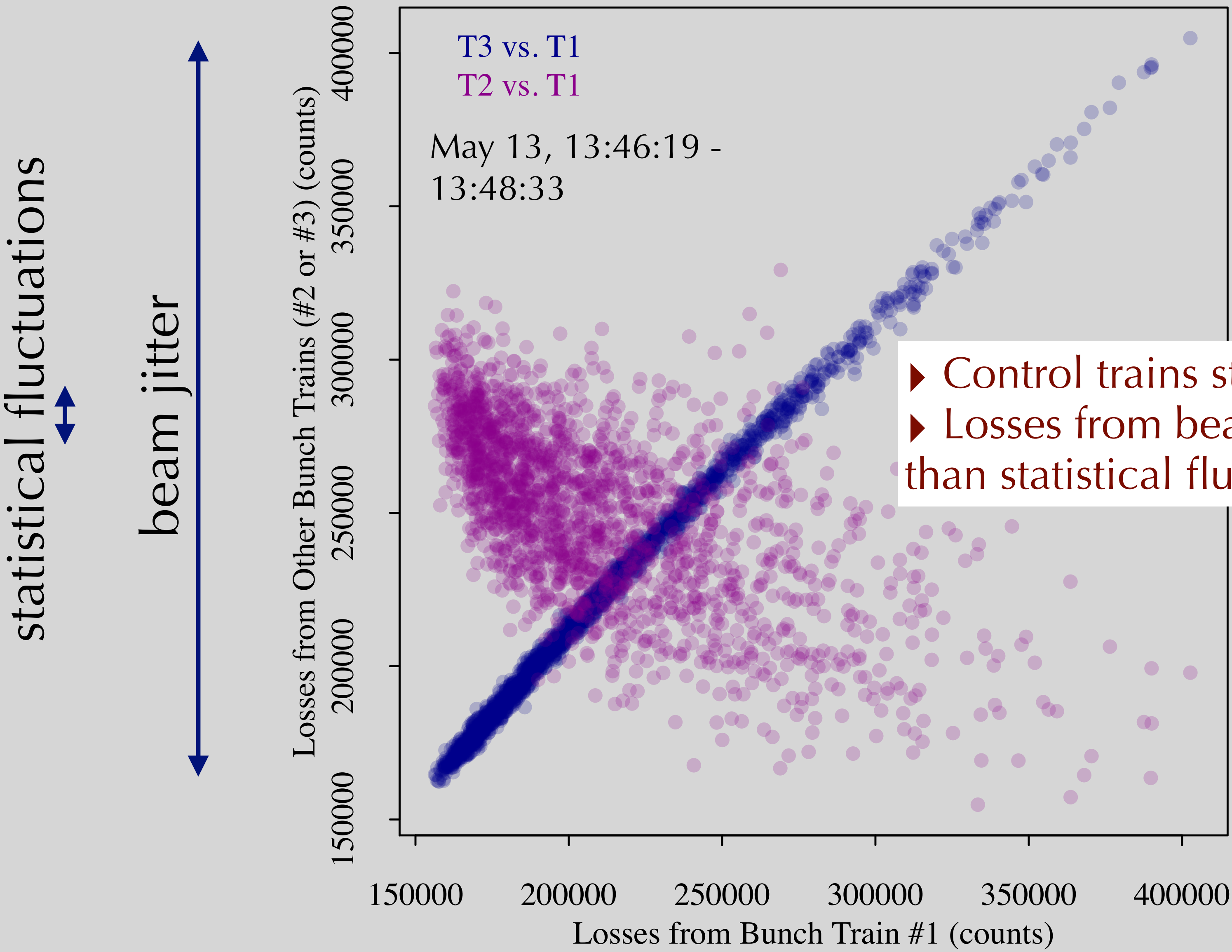


- Diffusion rate enhanced by factor ~10
- Halo population reduced
- Periodic losses suppressed

Fourier analysis of losses



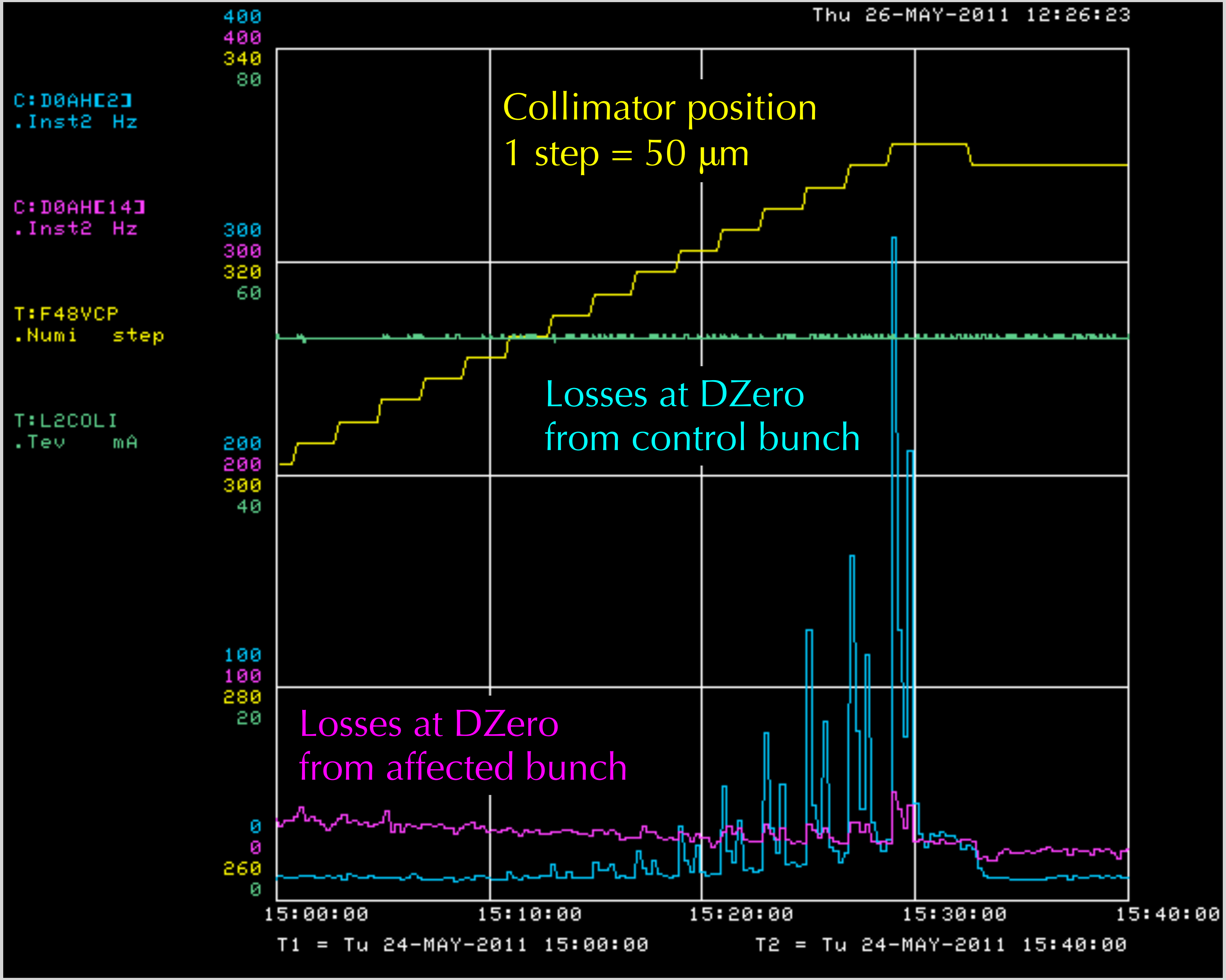
Correlation of steady-state losses



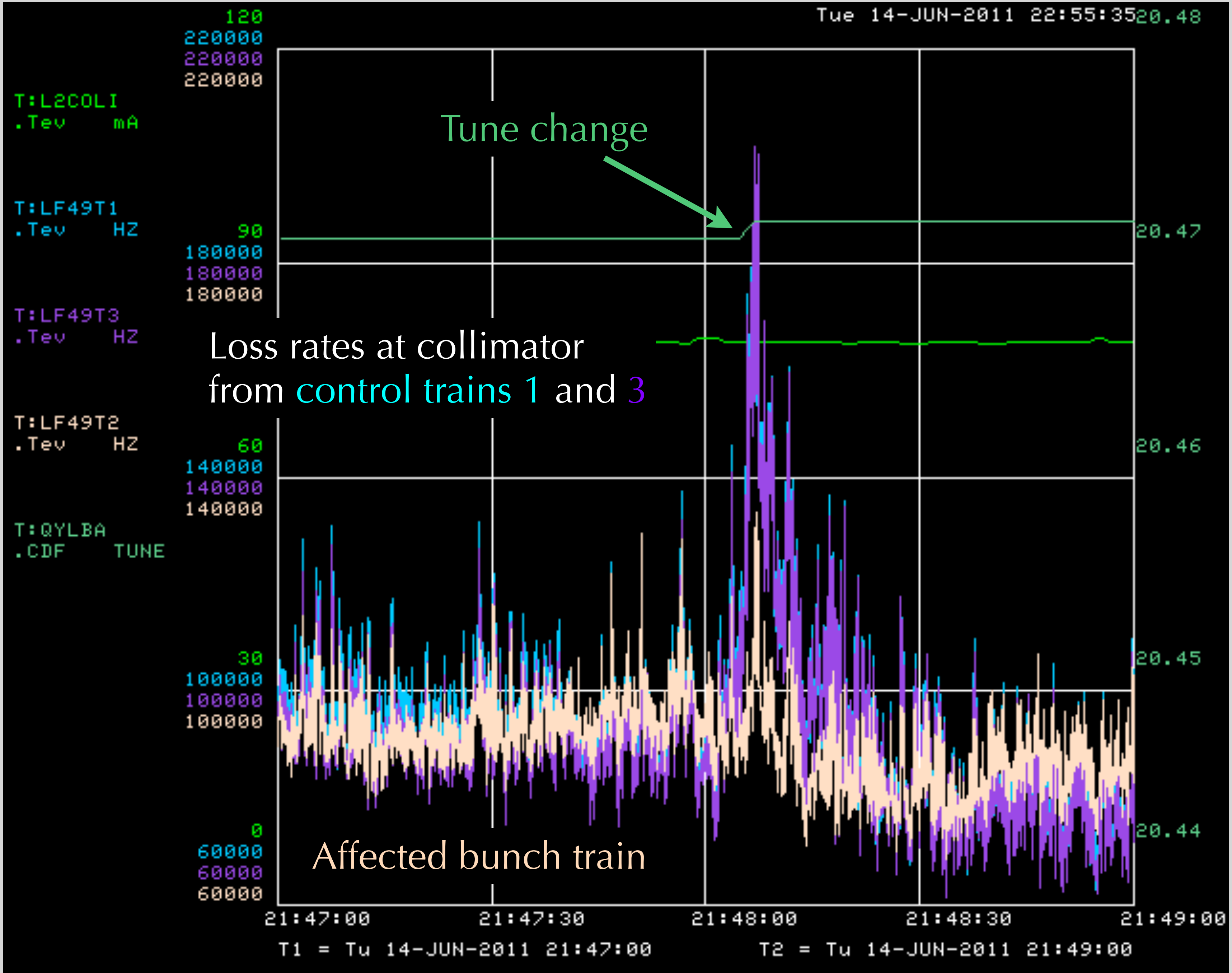
- Control trains strongly correlated
- Losses from beam jitter much larger than statistical fluctuations

- Hollow beam eliminates correlations among trains
- Interpretation: larger diffusion rate, lower tail population, less sensitive to jitter

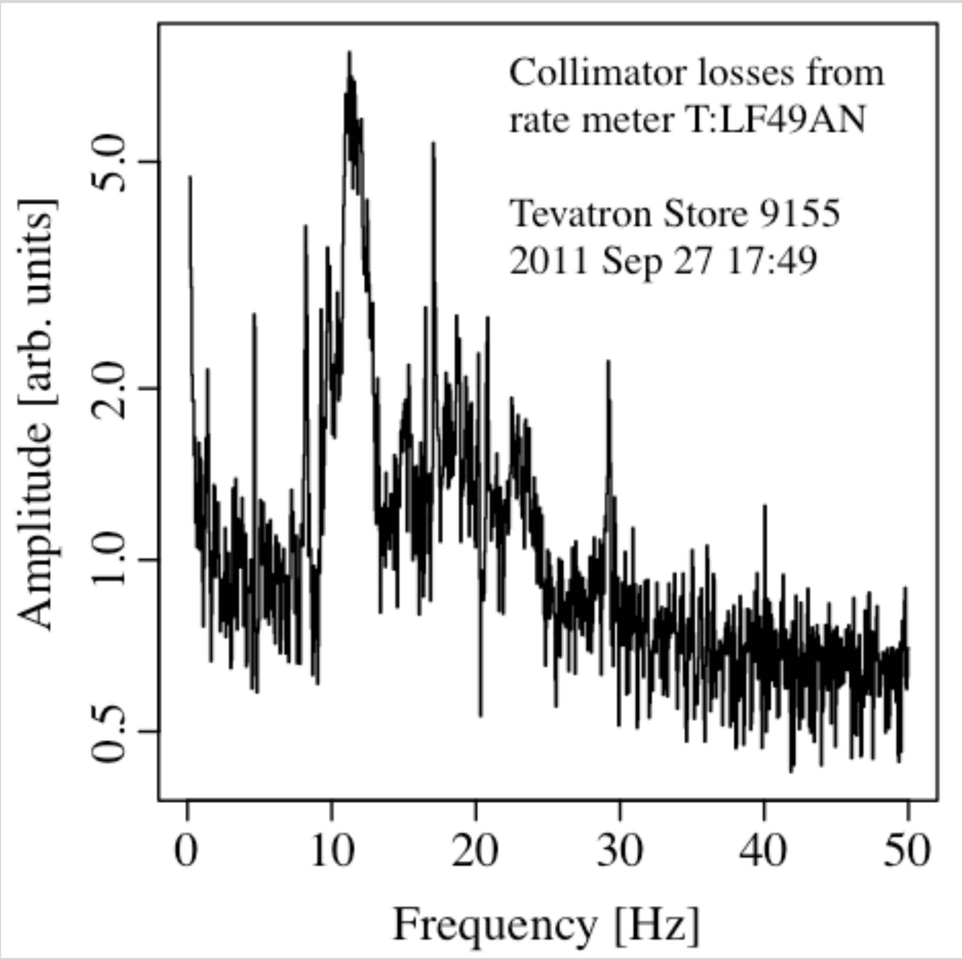
Suppression of loss spikes during collimator steps

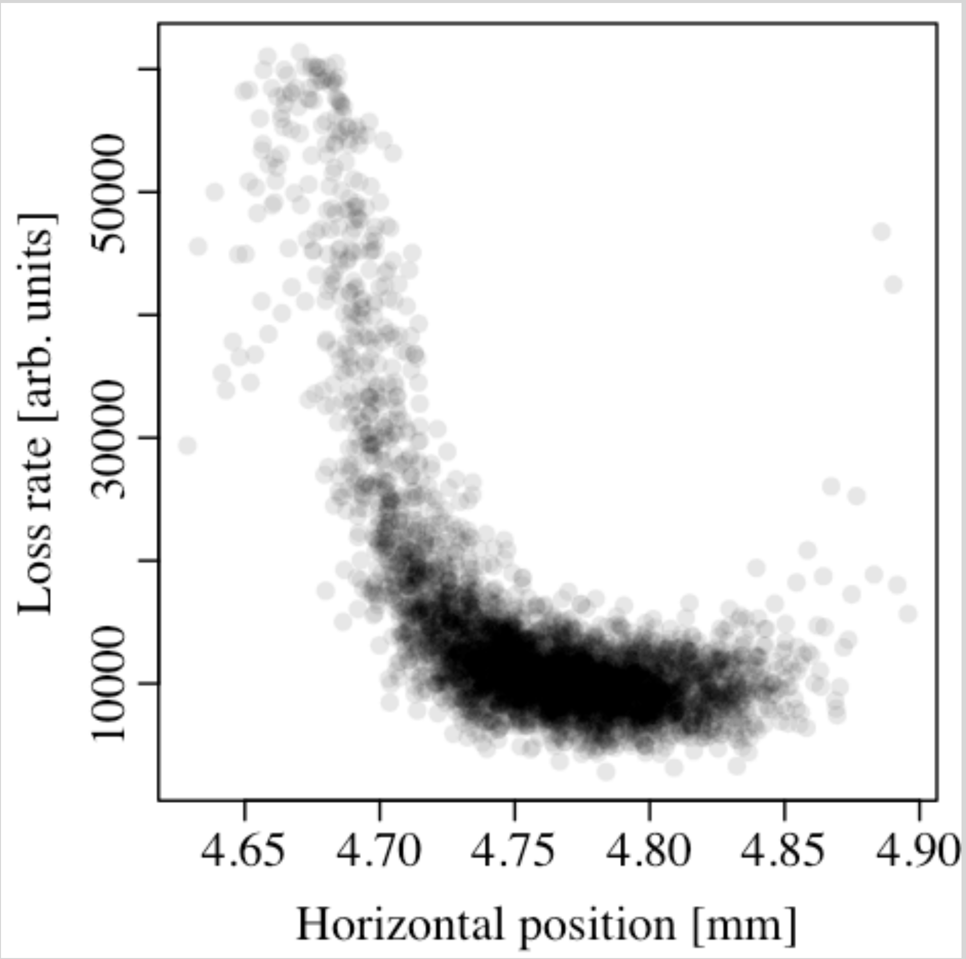


Suppression of loss spikes during tune change

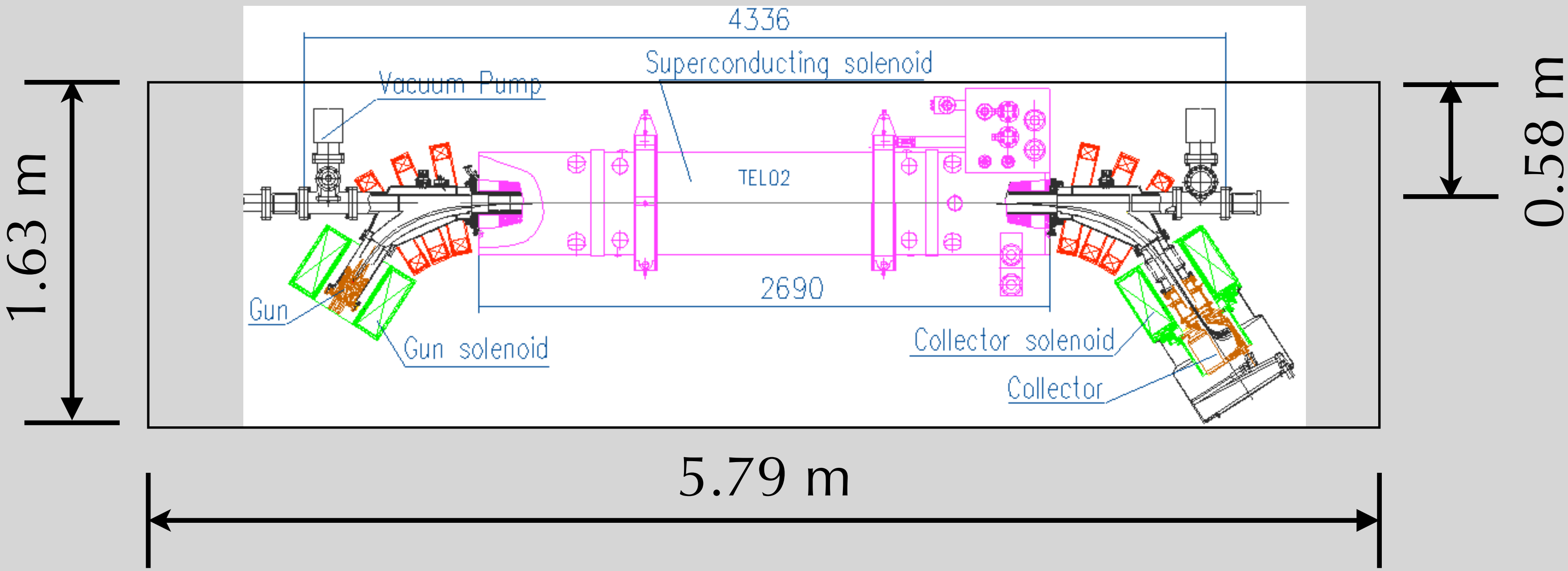


Beam jitter in the Tevatron



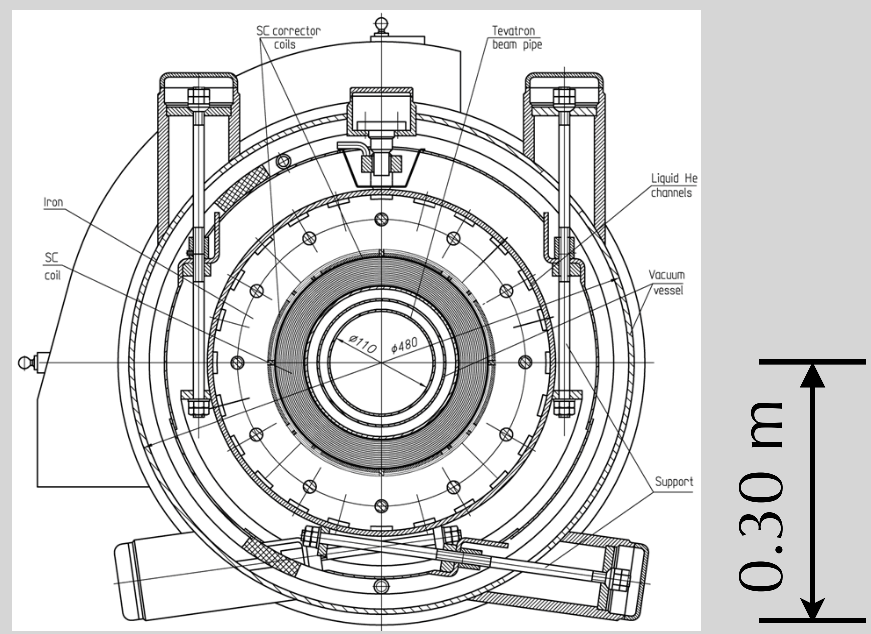


TEL2 dimensions

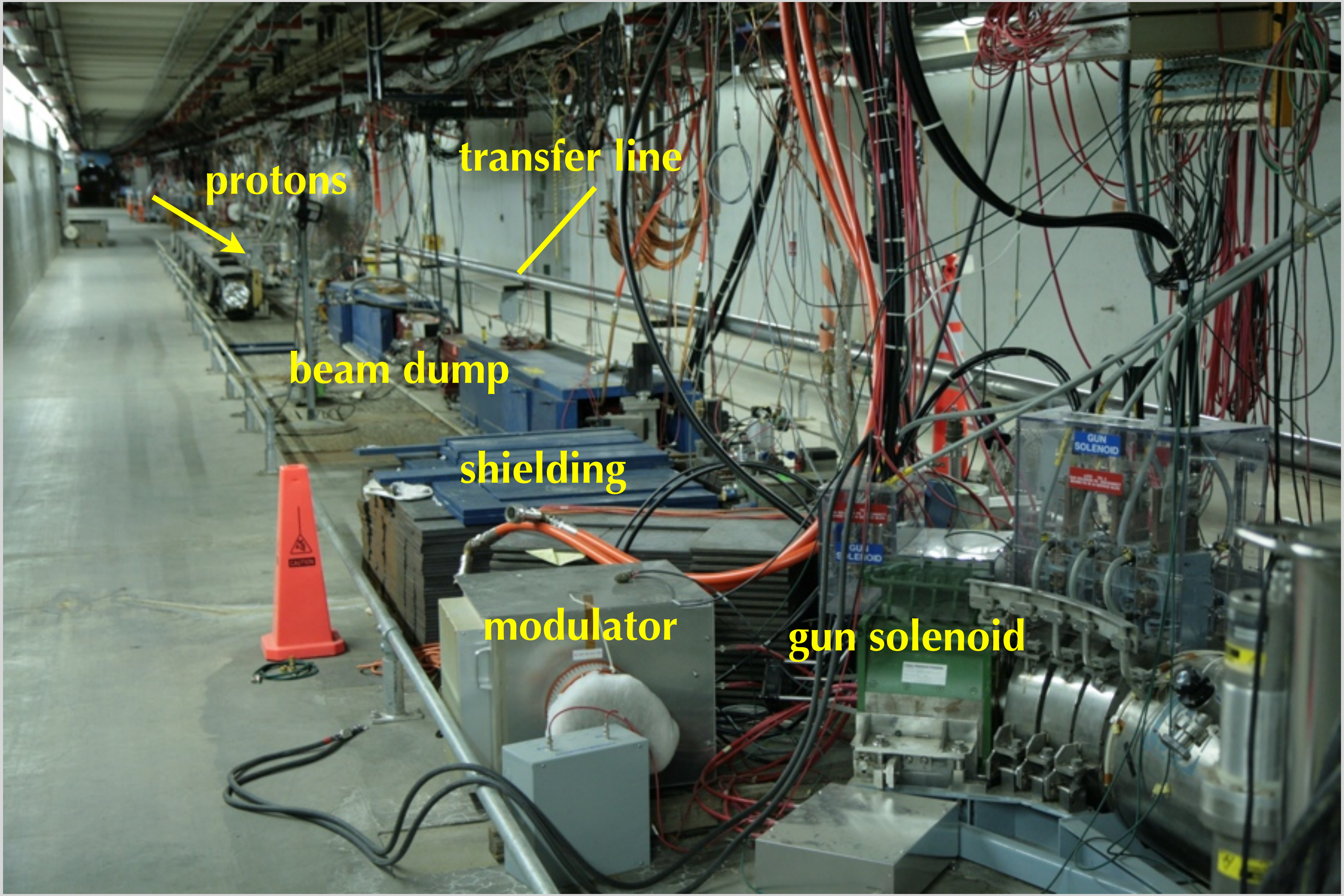


Height (including current and cryo leads): 1.47 m

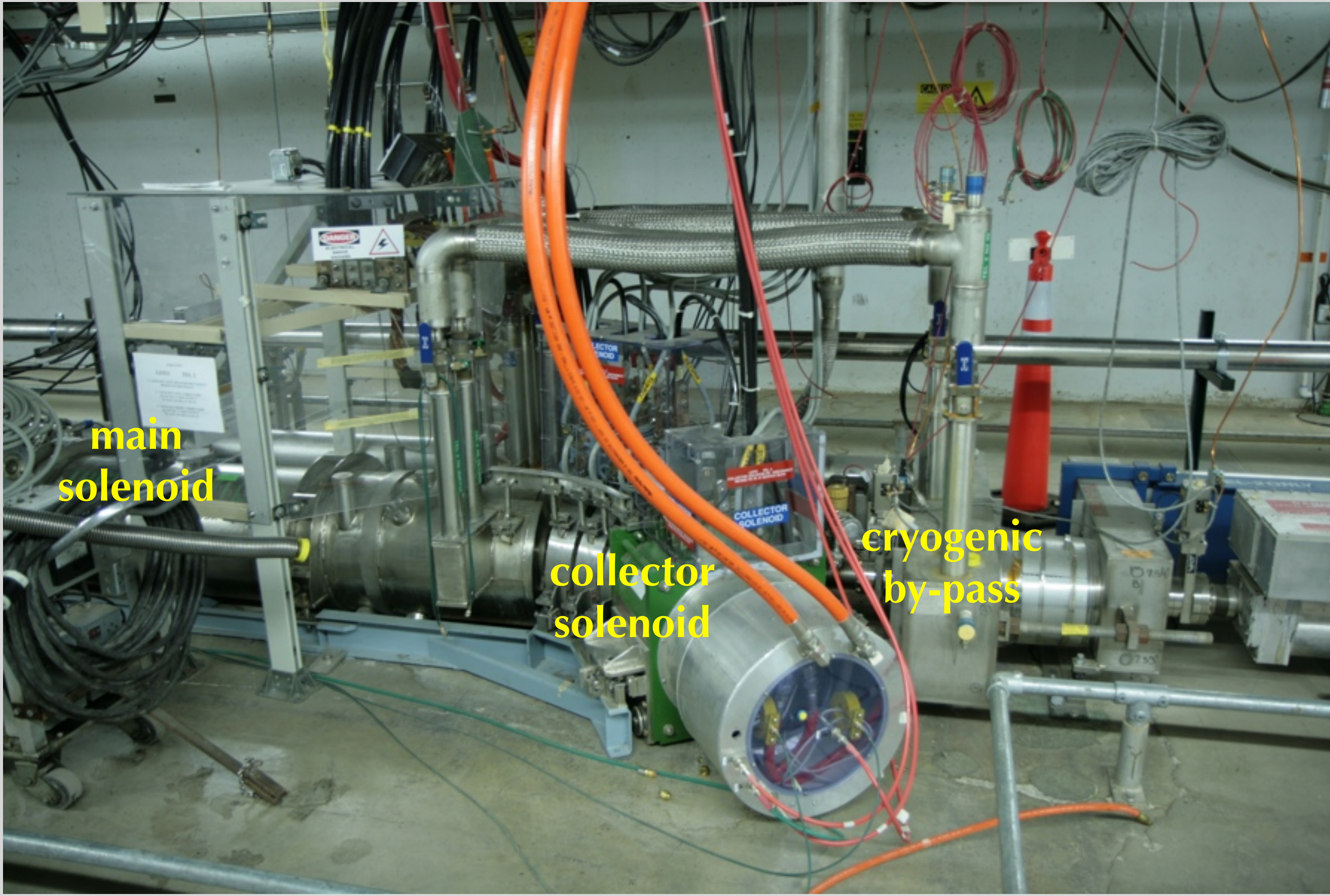
Weight: about 2 t



TEL2 photographs: gun side



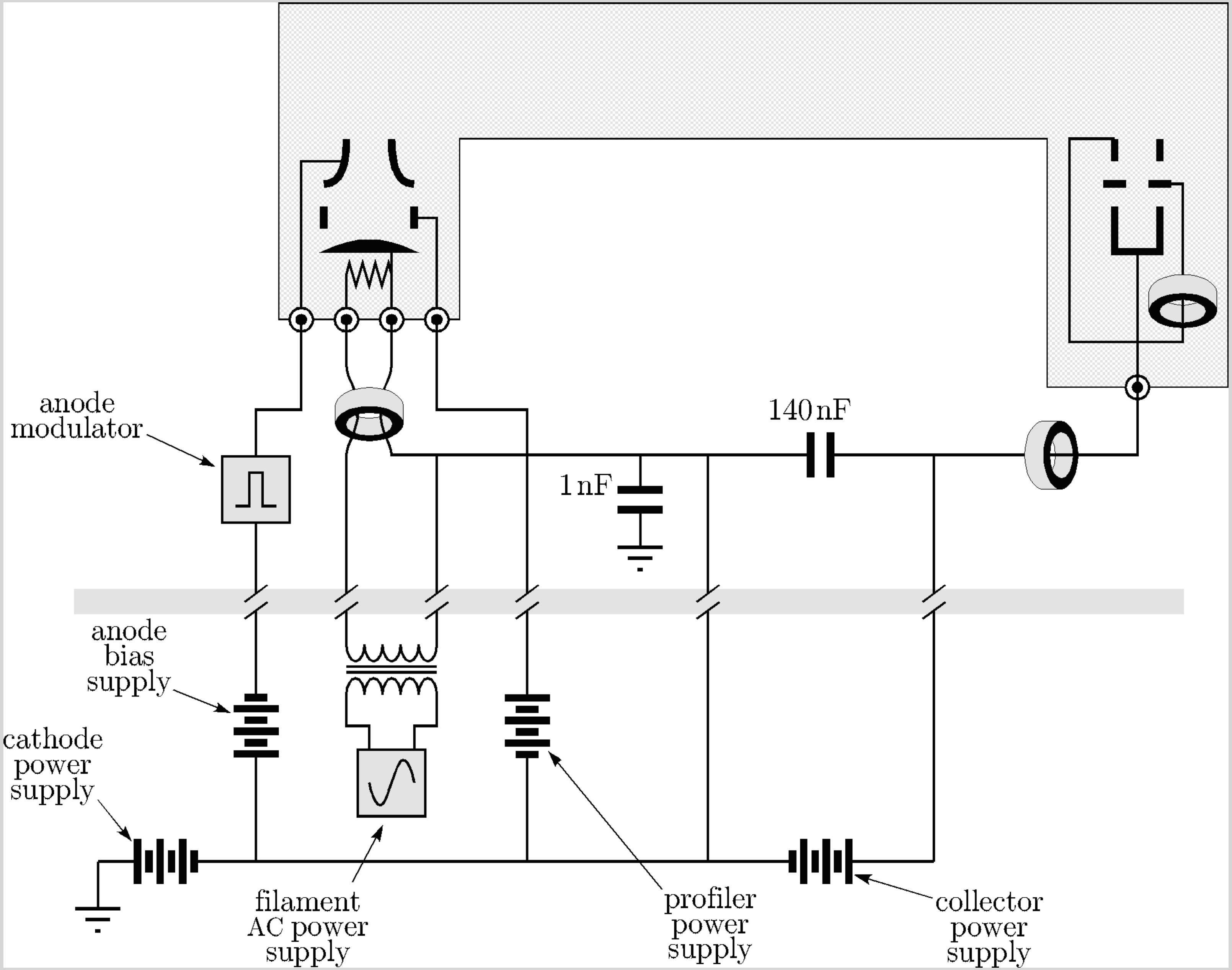
TEL2 photographs: collector side



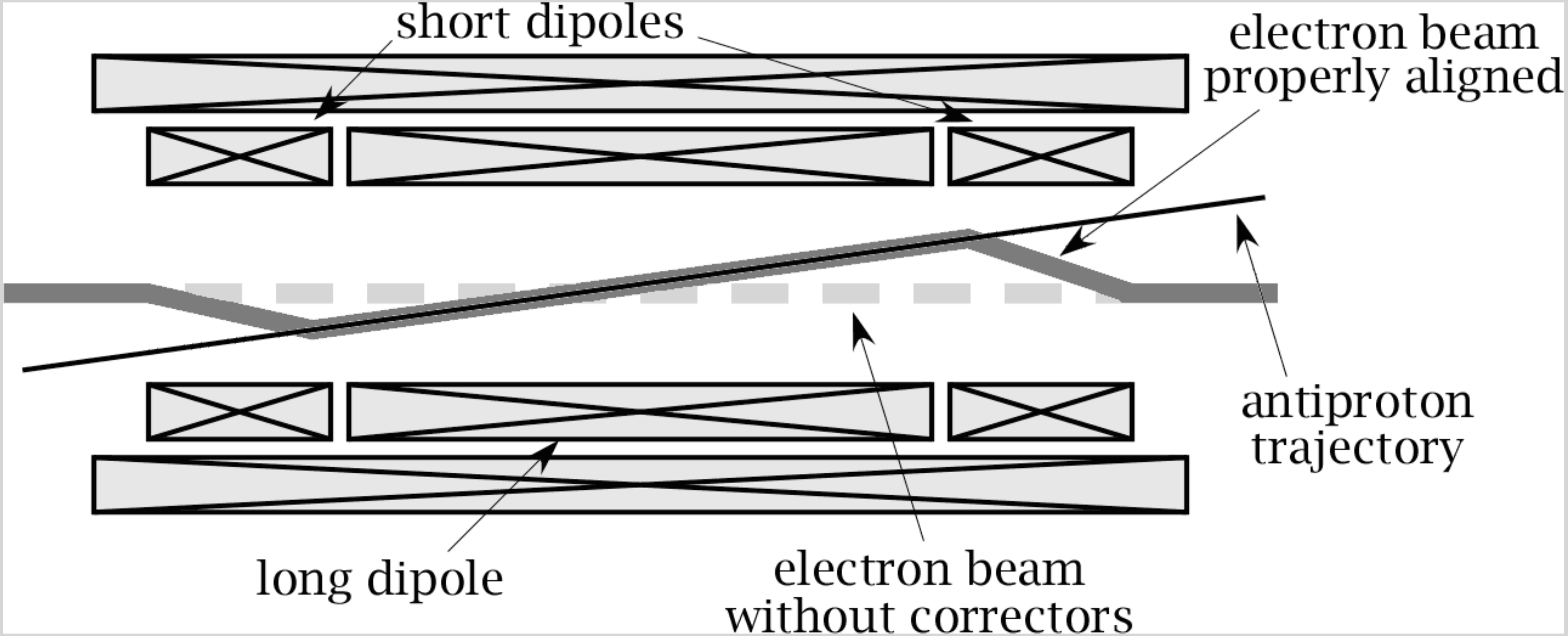
Principal subsystems

- Electrical
  - gun and collector solenoid power supplies: 340 A @ 0.4 T
  - main solenoid power supply: 1780 A @ 6.5 T
  - high voltage supplies for cathode, profiler, anode bias, collector: ~5-10 kV
  - stacked-transformer modulator, anode pulsing: 5 kV, 150 kHz, 200 ns rise time
- Vacuum
  - 10^{-9} mbar typical
  - 3 ion pumps + Ti sublim.
- Cryogenics (4 K)
  - static heat load: 12 W (helium vessel), 25 W (nitrogen shield)
  - Tevatron magnet string cooling system: 90 l/s of liquid He
  - quench protection
- Diagnostics
  - 6 corrector magnets inside main solenoid
  - 2 BPMs (each horiz.+vert.)

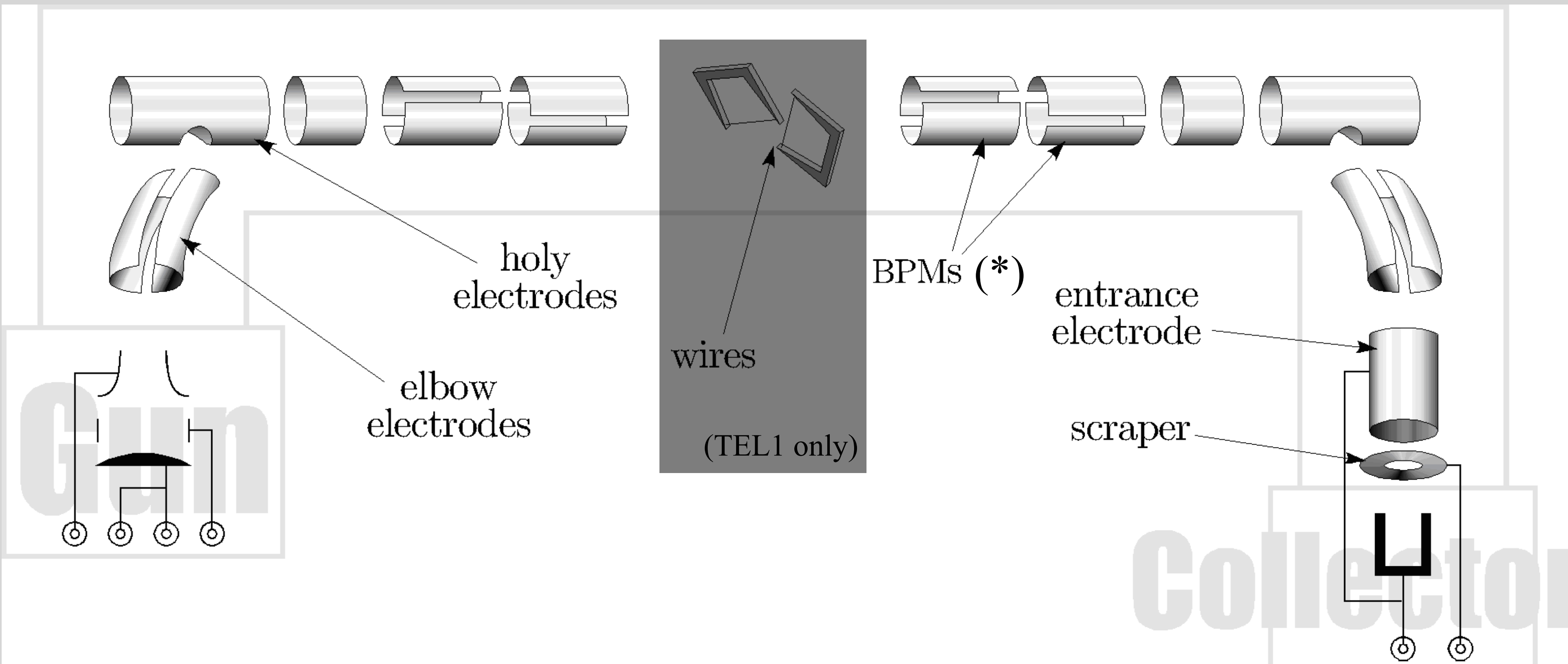
Tevatron electron lens: electrical schematic diagram



Tevatron electron lens: corrector dipoles

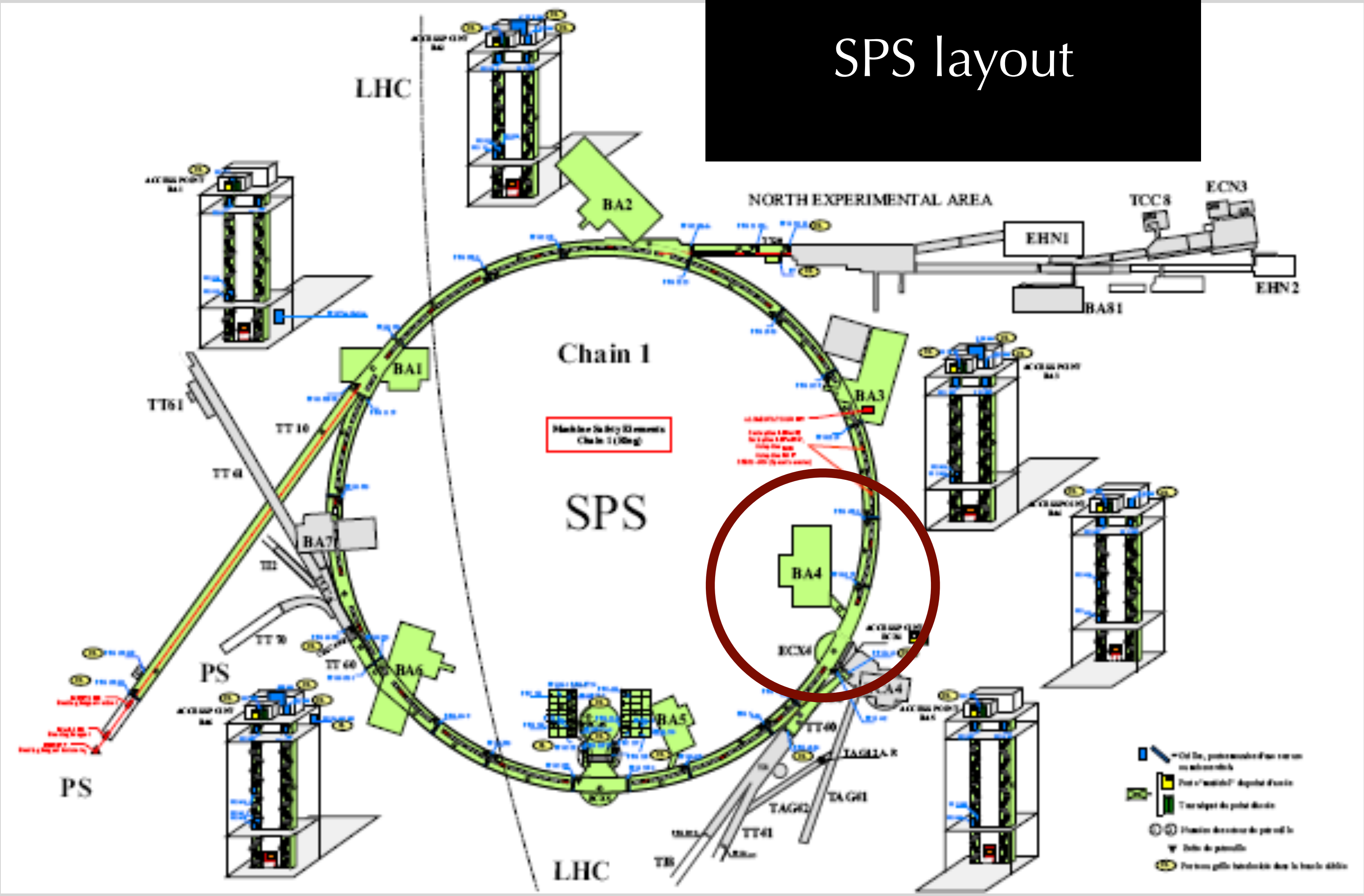


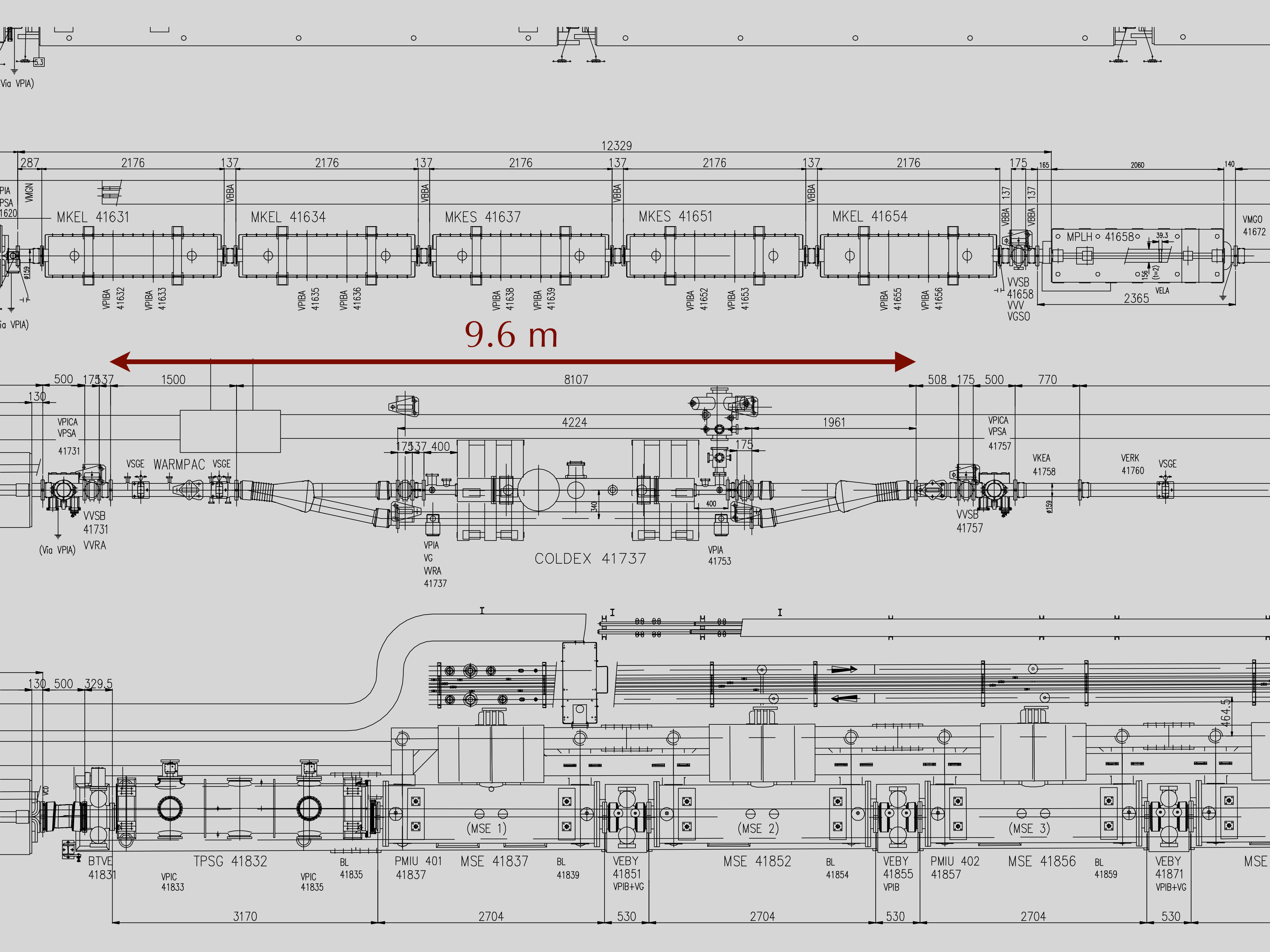
Tevatron electron lens: electrodes



(*) H and V BPMs combined in TEL2

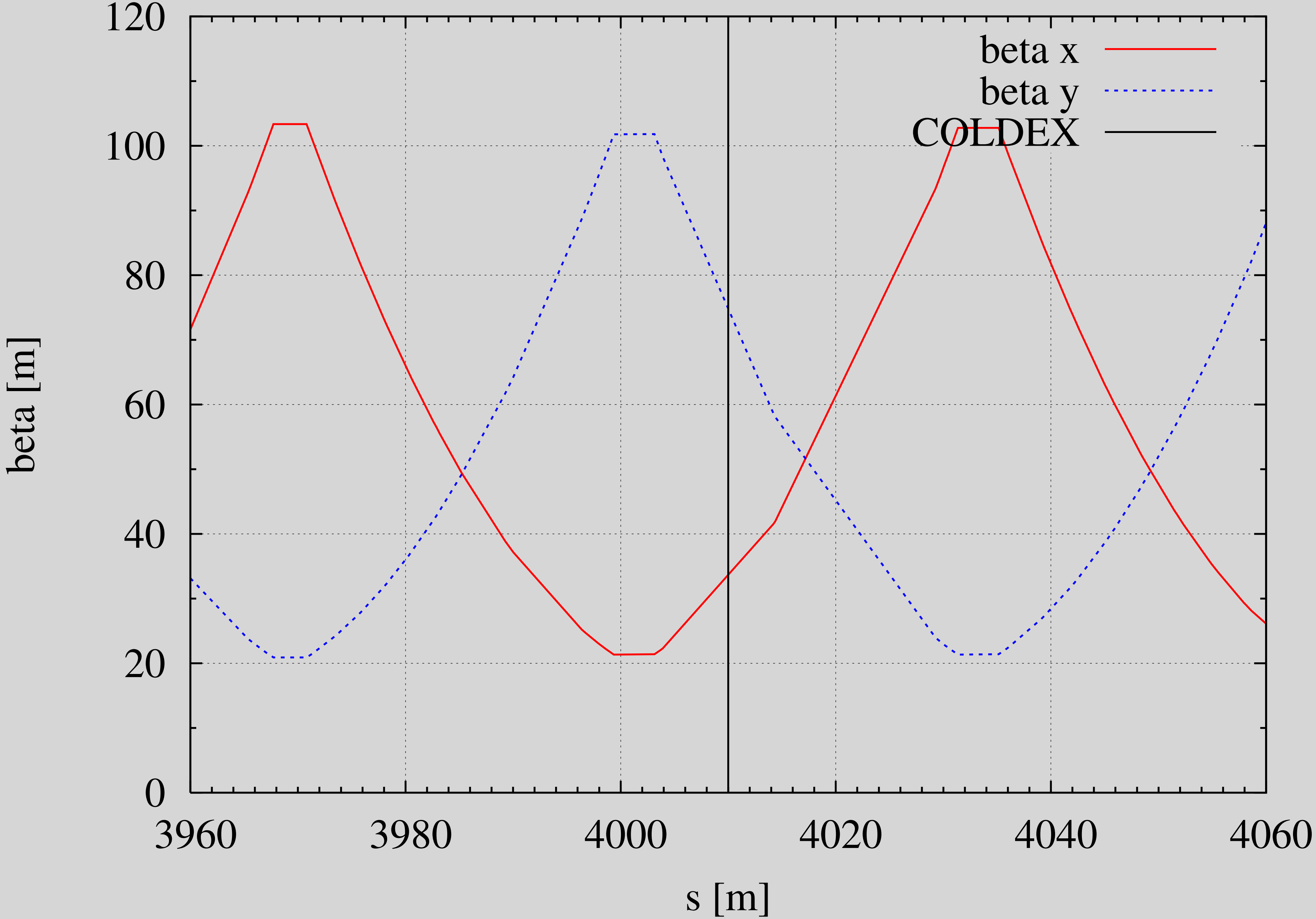
SPS layout


LHC
NORTH EXPERIMENTAL AREA
TCC8
ECN3
EHN1
EHN2
BA81
BA2
BA1
BA3
BA4
BA5
BA6
BA7
Chain 1
SPS
TT61
TT10
TT70
TT60
TT40
TT41
ECX4
TAG61
TAG62
PS
PS
LHC



12329
MKEL 41631
MKEL 41634
MKES 41637
MKES 41651
MKEL 41654
MPLH 41658
VVSB 41658 VVV VGSO
VMGO 41672
9.6 m
8107
4224
1961
VPICA VPSA 41731
VSGE
WARMPAC
VVSB 41731 VVRA
(Via VPIA)
COLDEX 41737
VPIA VG VVRA 41737
VPIA 41753
VPICA VPSA 41757
VVSB 41757
VKEA 41758
VERK 41760
BTVE 41831
TPSG 41832
VPIC 41833
VPIC 41835
BL 41835
PMIU 401 41837
MSE 41837
(MSE 1)
BL 41839
VEBY 41851 VPIB+VG
MSE 41852
(MSE 2)
BL 41854
VEBY 41855 VPIB
PMIU 402 41857
MSE 41856
(MSE 3)
BL 41859
VEBY 41871 VPIB+VG
3170
2704
530

Amplitude functions at BA4 in SPS



COLDEX installation overview looking downstream